Saturated hydraulic conductance of forest soils affected by track harvesters

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Abstract: The exact data from the field of soil mechanics from specific forest stands exposed to forestry mechanization operation were obtained. Field surveys were performed on four study plots within the Křtiny Training Forest Enterprise, Masaryk Forest, followed by laboratory analyses of the collected soil samples aimed at evaluation of the impacts of Zetor 7245 Horal System, PONSSE ERGO 16 harvester and Gremo 950 forwarder on the compaction of upper soil horizons as well as on the dynamics of soil saturated hydraulic conductivity. A specific objective of the performed investigation was to assess the influence of the used hauling/skidding technology on measurable parameters of soil mechanics with the emphasis on a possibility to apply the Guelph permeameter for direct study of soil saturated hydraulic conductivity. In the measurement points affected by machinery operation, the impact of the changed soil structure on the values of saturated conductivity is very well noticeable – on study plots No. 3 and 4, the values decreased by one order of magnitude from 0.7×10^{-5} m·s^{-1} to 0.09×10^{-5} m·s^{-1}: specifically, (*i*) on study plot No. 3 and from 6.9×10^{-5} m·s^{-1} to 0.7×10^{-5} m·s^{-1}, and (*ii*) on study plot No. 4; on study plot No. 2 even by two orders, i.e. from 1.6×10^{-5} m·s^{-1} up to 0.03×10^{-5} m·s^{-1}. After the operation of a universal wheeled tractor at the Babice nad Svitavou locality, the situation partially improved by one order to 0.3×10^{-5} m·s^{-1}, similarly like at the Rudice locality to 1.5×10^{-5} m·s^{-1}. Significant changes were found in both surface and subsurface horizons. Field-saturated hydraulic conductivity indicates also a reduction of the pore volume after machinery traffic; however, tendencies towards restoration of the original state were detectable as soon as after six months.

Keywords: forest soil; saturated hydraulic conductivity; hauling technology; Guelph permeameter

The total area of forest stands in the Czech Republic is 2,653,033 ha, which represents 33.64% of the area of the Czech Republic. In 2008, 16.2 million m^3 of raw timber were harvested from the total stock of 676.4 million m^3 of raw timber with the average standing volume of 260.4 m^3 of raw timber per 1 ha of stand area, including clearcuts (Report on the State of Forest and Forestry in the Czech Republic in 2008, 2009). The significance of the presented numbers is important from the aspect of the influence on the state and dynamics of forest soil development as harvested timber is hauled or skidded from the stands by methods with very different impacts on soil. Information from the Report on the State of Forests and Forestry in the Czech Republic by 2009 shows that almost one third of the annual cut is processed by the shortwood logging method (the rest by the tree-length logging method) and that all raw timber was transported for further handling or processing from the regenerating

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forest stands by a universal wheeled tractor with a winch (UWT/UKT), special forest prime mover (SFPM/SLKT), forwarder or by a cableway installation. However, cableway installations are presently employed in the transport of less than 350,000 m^3 of timber per year in the Czech Republic due to low effectiveness of their use and complexity of the whole technological procedure, which leads to practically full-area employment of UKT and SLKT with such potentially serious impacts on forest soils that research on the relation between forestry hauling technologies and soil mechanics is inevitable.

A specific goal of the investigation presented in this paper was to assess the impacts of the applied hauling/skidding technology on measurable parameters of soil mechanics with special focus on the possible application of a Guelph permeameter for direct study of soil saturated hydraulic conductivity dynamics. The field surveys were combined with standard soil-physical laboratory methods (Rejšek et al. 2010), with the objective to detect any changes in physical, hydrophysical and soil-mechanical properties of forest soil in reaction to logging and hauling machinery operations. The soil conditions at the individual localities were described by the basic physical, physicochemical and chemical properties of the individual horizons, obtained from open soil profiles (Dundek et al. 2010). Within the field survey, saturated hydraulic conductivity was measured with a Guelph permeameter: the aim of the author team was to use the obtained data to assess changes in the conditions for pedogenetic processes in the upper soil horizons. Simultaneously, repeated measurements with a dynamic permeameter and sampling of the examined forest soil profiles with uniform metal cylinders were carried out.

Saturated hydraulic conductivity of forest soils affected by the operations of a universal wheeled tractor Zetor 7245 Horal System, PONSSE ERGO 16 harvester and Gremo 950 forwarder on selected study plots within the Křtiny Training Forest Enterprise, Masaryk Forest, was investigated by laboratory analyses aimed at the basic physical and hydrophysical methods as well as by a field survey with the application of a Guelph permeameter (Reynolds, Elrick 1985). From the aspect of forestry, saturated flow is not of key importance, contrary to the state of steady flow depending on water sorbents. Therefore, we differentiate between the stationary flow with flow speed and moisture content that are constant in time, and non-stationary flow with changing speed and soil moisture content (Homolák et al. 2010). The flow can be further classified according to the saturation of pores with water as saturated flow, filling up all the pores, and non-saturated flow, where some of the pores are filled up with air and so the soil can further saturate with water, or reversely drain (Rehák et al. 2006). Morphology and structure affected by compaction have a fundamental significance for hydraulic conductivity as well as water, air and heat regimes. The authors of this paper have focused on stationary saturated flow since it can indicate the changes of soil physical properties due to machinery traffic and at the same time its measurement is easy to perform within forestry research (Lhotský 2000).

Saturated hydraulic conductivity is nowadays measured either in a laboratory (cylindrical samples of soil) or by field measurements. However, analyses performed on sampled soil are less accurate as the sampling and transport may change some important properties. The dynamics of saturated hydraulic conductivity of soil is expressed by the coefficient Kfs and evaluated on the basis of field experiments. This characteristic is measured either by a single-well test or by so-called auger-hole method, in relation to the instantaneous depth of the groundwater level: if the groundwater level is close to the surface, a hole is bored to a specified depth under the water level; after measuring the hole's depth and the water level, water is pumped out and the rise rate of the groundwater in the hole is determined with a float and a stopwatch. If it is not possible to reach the water level in this way, Kfs is determined by a pump-in test with a Guelph permeameter. In this case, the rate of water discharge from the apparatus into the hole is read at regular time intervals until stationary flow is reached, i.e. the rate of flow through the hole is constant (Kutílek et al. 1996). An advantage of this method is that only few variables are necessary for Kfs calculation, consumption of water is low and the equipment needed to perform the measurement is simple.

MATERIAL

Parameters of operating machines

Zetor 7245 Horal System. Universal wheeled tractor with 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. The pressure recommended by the manufacturer is 240 kPa for the front tyres and 200 kPa for the rear tyres. 60% of the weight of the tractor act upon the rear axle. The total weight of the tractor with the forestry body (front platform loader, shield with a winch and safety frame) is about 5 t.

PONSSE ERGO 16 harvester. A three-axle harvesting machine designed with maximum attention to the low impact of operations on forest stands.

It is equipped with a tilting cabin with antivibration equipment, a modern hydraulic system of all wheel drive and an electronic control unit (front tyre dimensions 700/50-22.5“, rear tyre dimensions 700/55-34“. The tyres were not fitted with any supplementary devices such as tracked wheels or non-skid chains. The total weight of the machine (depending on the equipment used) is about 16 t.

Gremo 950 forwarder, A four-axle universal forwarder Gremo 950 is designed for the low-impact extraction of timber after harvester logging. The rear part of the machine has a capacity to carry up to 4.1 m^3 of timber, load capacity 9.5–10 t. Timber is loaded with a hydraulic crane placed traditionally in front of the loading space. The electronically controlled hydrodynamic drive of all wheels ensures the smooth operation of the machine without wheel spinning. Service weight of the machine is almost 12 t. The forwarder was equipped with Nokian tyres of 700 × 22.5“ at all axes. All wheels of the forwarder were fitted with non-skid chains.

Measurement equipment used in field surveys

Guelph permeameter (constant head permeameter). The device works on the principle of Mariotte bottle (Kutílek et al. 2000), i.e. it maintains the constant head of water at the outlet by means of a negative-pressure air cushion that forms above the liquid level. The permeameter consists of a water reservoir and an outlet with perforated bottom and walls. A hole of 2 to 5 cm in diameter and depth up to 1 m is bored into soil and the outlet part is inserted; the authors used a hole of 3 cm in diameter and of 15 cm in depth. By raising the air tube, the level of water in the hole was set and gradual outflow of water from the reservoir began. The rate of the water level decrease in the reservoir was measured until stationary flow Q ($m^3 \cdot s^{-1}$) was reached.

The following equation by Kutílek et al. (2000) was used for the evaluation:

$$Kfs = \frac{cQ}{(2\pi H + c\pi r)}$$

where:

c – non-dimensional factor depending on texture and H/r ratio (c ± 1.59),

Q – stationary value of water flow from the permeameter,

r – radius of the bored hole,

H – level of water in the hole.

Study plots

The survey was carried out on four 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 with clear-cutting system of management. Generally we can say that the study plot in Babice nad Svitavou represented the group of forest types 3A, i.e. lime-oak beech forest, and according to the framework management guidelines it represented the management set of stands 306 Special-purpose beech management of drying and drier acerous and basic sites at medium altitudes. In Rudice, the study plots belonged to the group of forest types 4K, i.e. acidic beech stands, the management set of stands 421 Special-purpose spruce management of acidic sites at medium altitudes.

Field surveys

Soil pits were described at all four localities, sampling of physical cylinders and subsequent analyses were performed only at localities No. 2–4. In order to obtain the overall characteristic of soil conditions, the following properties were determined: physical (grain size, density, bulk density and wet bulk density, maximum capillary water capacity, porosity, volume and weight moisture, aeration, minimum air capacity, relative capillary moisture, relative saturation of pores and dry matter content), physicochemical (active soil reaction, reserve/potentially exchangeable soil reaction, base saturation, cation exchange capacity, content of exchangeable base cations) and chemical (content of oxidizable carbon, total nitrogen content and C:N ratio). To assess the impact of forestry mechanization traffic, physical properties and saturated hydraulic capacity were measured repeatedly.

In order to obtain detailed characteristics of soil properties, a soil pit 110–120 cm in depth was excavated on each plot in a place reflecting natural conditions in the specific stand. Its position was chosen on the basis of terrain reconnaissance and evaluation of potential influences affecting the specific plot. The terminology from the Taxonomic Soil Classification System of the Czech Republic (Němeček et al. 2001) and the Munsell system of colour notation of soil horizons were applied for description of soil profiles.

Undisturbed samples, i.e. samples with unchanged macrostructural features, from the described horizons were taken with uniform metal cylinders of 100 cm^3 in volume. In addition, the soil profiles of the study plots were sampled and analysed in laboratory using standardized procedures (Rejšek 1999). At the same time, field measurements of saturated hydraulic capacity Kfs with Guelph permeameter were performed.

The collection of physical cylinders from the first three diagnosed soil horizons and the permeameter measurements were repeated shortly after a harvesting operation and again 6 months later, i.e. in October 2007, April 2008 and October 2008. Due to different physiological depth of soil, the physical samples were collected from the first three diagnosed horizons, beginning with the organomineral horizon, where the most significant impact of machinery traffic is expected. The plots were divided by harvesting into areas with ongoing operations and areas where the stand was left without intervention. The measurements were divided into control measurements monitoring the seasonal dynamics of the studied characteristics and measurements in the places of machinery traffic. Therefore, two measurements were performed on each study plot: one in a place exposed to multiple traffic of machinery and the other in a control place, intact by any machinery operation or its influence. Values of water flow rate v into the soil profile were read each minute, until stationary flow

Table 1. Properties of particular soil horizons, study plot No. 2, Babice nad Svitavou, universal whelled tractor Zetor 7245

No. of forest stand: 314B10; District in Masaryk Forest Křtiny: Bílovice; Hauling machine: UWT; Pedogenetic substrate: decalcified loess; Soil group: Luvisol; Soil subunit: Haplic; Code: haLV

Horizon	Ah	Designation of a property	El	Designation of a property	Bt	Designation of a property
Soil physics						
2–0.25	2.36	sandy loam	2.20	sandy loam	3.20	clay
0.25–0.1	2.98		2.18		1.20	
0.1–0.05	10.34		14.94		12.24	
0.05–0.01	50.08		43.2		27.76	
0.01–0.002	18.32		19.12		12.20	
> 0.002	15.92		18.36		43.40	
Maximum capillary capacity Θ_{MKK}	25.97	waterholding	30.74	strongly waterholding	36.74	strongly waterholding
Moisture content by mass w	27.25	moderately wet	17.07	moderately wet	21.05	moderately wet
Wet bulk density ρ_w	0.94	–	1.53	–	1.87	–
Bulk density ρ_d	0.74	–	1.30	–	1.54	–
Density ρ_s	2.24	–	2.59	–	2.79	–
Porosity P	67.15	high	49.72	moderate	44.67	low
Moisture content by volume Θ	20.07	–	22.24	–	32.44	–
Soil aeration A	47.08	–	27.48	–	12.23	–
Minimal air capacity A_{MKK}	41.18	very highly aerated	18.98	moderately aerated	7.93	low aerated
Relative soil moisture R_V	77.28	–	72.35	–	88.3	–
Relative saturation R_{NP}	29.89	–	44.73	–	72.63	–
Soil physicochemistry						
pH/H_2O	4.23	moderately acid	4.49	moderately acid	6.49	neutral
pH/KCl	3.71	strongly acid	3.51	strongly acid	5.34	moderately acid
Cation exchange capacity T	38.1	very low	67.5	very low	101.7	low
Content of exchangeable basic cations S	10.1	very low	50.9	low	98.3	moderate
Base saturation V	26.6	unsaturated	75.5	moderately saturated	96.7	highly saturated
Soil chemistry						
C_{ox}	8.50	very high content of humic compounds	1.75	high content of humic compounds	1.05	low content of humic compounds
N_t	0.469	very high	0.104	moderate	0.096	moderate
C:N	18.1	–	16.8	–	10.9	–

Q was reached, which was then used to calculate the saturated hydraulic capacity Kfs of the specific soil.

Results from study plot No. 2 are linked to a skidding trail with the total of 5 passes of the universal wheeled tractor Zetor 7245 Horal that transported 12 m^3 of timber in semi-suspension. It is necessary to take into account that the stand 314B10 had been previously prepared for regeneration with a release cutting measure, and so the harvesting and skidding operations did not involve high volumes of timber, but rather required frequent traffic of the tractor. The control measurements were performed 15 m from the testing trail in a young stand unaffected by the described tractor operations. The exact characterisation of the soil units on the plot is given in Table 1.

On study plot No. 3, harvester thinning was carried out in order to open up the stand, which is classified as a source of reproductive material for spruce and larch in the phenotype category B. Within the operation, 560 m^3 of timber were harvested, both roundwood assortments and pulpwood. A three-axle PONSSE ERGO 16 harvester was used for the opening up operation and the following haulage was performed by a four-axle Gremo 950 forwarder. The exact characterisation of the soil units on the plot is given in Table 2.

On study plot No. 4, motor-manual thinning was carried out. The following extraction and skidding works were performed by a universal wheeled tractor Zetor 7245 Horal with forestry body. 16.4 m^3 of raw timber were harvested in total. The exact characterization of the soil units on the plot is given in Table 3.

Laboratory analyses

Analyses were performed in the laboratories of the Department of Geology and Pedology at the Faculty of Forestry and Wood Technology, Mendel University in Brno, separately for the uniform metal cylinders and for the soil samples as such. After assessing the content of water and dry matter in the samples with the original moisture content, the samples were dried out for other standardised procedures (Rejšek 1999). The proportion of the individual particle size fractions in a sample was assessed by a pipetting method, when 20 g of a sample are mixed with 20 ml of dispersing medium and 20 ml of distilled water, the mixture is left to stand for one day and then boiled for one hour. The dispersed solution is transferred into a sedimentation cylinder and distilled water is added up to 1,000 ml. The suspension is stirred up for 1 min, after which the sedimentation time measurement begins. The samples of the suspension are pipetted with a 25 ml volume pipette at the depth of 25 cm at the time of 10 s, at the depth of 10 cm at 12.5 s and at the depth of 7 cm at 15 s in compliance with the appropriate time data, i.e. with both time after the end of stirring and time before the end of sedimentation. Particles of diameter < 0.05 mm are found at the depth of 25 cm at the time of 112 s from the beginning of measurement, particles < 0.01 mm are at the depth of 10 cm at 18 min 51 s and particles < 0.001 mm may be pipetted at the depth of 7 cm after 22 h 6 min 12 s from the beginning of measurement. The analysis of uniform metal cylinders began by weighing in the original state, in the water-saturated state after 24 h, in the state after saturation with the frequency of 90 min and again after being re-dried at 105°C (Zbíral et. al. 2004). Density was determined pycnometrically. The remaining basic chemical and physical-chemical properties were assesseh by methods according to Rejšek (1999), including calculations of the basic physical characteristics.

RESULTS

The basic physical and hydro-physical properties of the individual soil horizons of the soils from the study plots are presented in both tables and figures: for study plot No. 2 (Table 4 and Fig. 1), for study plot No. 3 (Table 5 and Fig. 2), and for study plot No. 4 (Table 6 and Fig. 3).

In general, the authors have proved that the soils on study plots No. 3 and 4 collectively show sandy silt loam and clay loam in surface horizons to silty clay and clay in horizons Bt (very heavy grain size composition). Porosity and aeration decrease with depth at locality No. 3 up to the category "nonarerated" in E/B horizon. In surface horizons a strong acidity (low pH/H_2O), the maximum capacity of the sorption complex is very low and extremely unsaturated to saturated (towards the Bt horizon) for all horizons. As regards the chemical properties, the soils found on study plots No. 3 and 4 are humic with medium nitrogen content and, compared to the study plots at thy Babice nad Svitavou locality, with higher C:N ratio, corresponding to the quality of the organic matter entering the soil, i.e. corresponding to the fact that common spruce (*Picea excelsa* [L.] Karst.) is the main commercial species there. Regarding the dynamics of change of the field saturated hydraulic conductivity Kfs, the original measurementt detected changes caused by the machinery traffic (the section Discussion

Table 2. Properties of particular soil horizons, study plot No. 3, Rudice, the harvestor PONSSE ERGO 16 and the forwarder Gremo 950

No. of forest stand: 146D7; District in Masaryk Forest Křtiny: Habrůvka; Hauling machine: Harvestor; Pedogenetic substrate: decalcified loess; Soil group: Luvisol; Soil subunit: Haplic; Code: haLV

Horizon	Ah	Designation of a property	El	Designation of a property	EB	Designation of a property	Bt	Designation of a property
Soil physics								
2–0.25	3.05	sandy loam	3.36	sandy loam	22.24	sandy clay	1.47	clay
0.25–0.1	2.14		2.030		1.25		0.88	
0.1–0.05	13.45		12.61		8.83		10.21	
0.05–0.01	46.16		46.56		35.36		22.40	
0.01–0.002	18.36		18.64		15.44		13.92	
> 0.002	16.84		16.80		37.04		51.12	
Maximum capillary capacity Θ_{MKK}	25.68	waterholding	28.90	waterholding	34.49	strongly waterholding	41.75	strongly waterholding
Moisture content by mass w	12.78	dry	12.87	fairly moist	18.37	moderately wet	21.01	fairly moist
Wet bulk density ρ_w	1.30	–	1.44	–	1.92	–	1.97	–
Bulk density ρ_d	1.16	–	1.27	–	1.62	–	1.63	–
Density ρ_s	2.42	–	2.59	–	2.65	–	2.83	–
Porosity P	52.23	moderate	50.80	moderate	38.85	low	42.39	low
Moisture content by volume Θ	14.78	–	16.40	–	29.79	–	34.25	–
Soil aeration A	37.45	–	34.40	–	9.06	–	8.14	–
Minimal air capacity A_{MKK}	26.55	highly aerated	21.90	highly aerated	4.36	very low aerated	0.64	very low aerated
Relative soil moisture R_V	57.55	–	56.75	–	86.37	–	82.04	–
Relative saturation R_{NP}	28.30	–	32.28	–	76.68	–	80.80	–
Soil physicochemistry								
pH/H_2O	3.87	strongly acid	4.14	moderatedly adic	5.20	slighly acid	7.32	slightly alkaline
pH/KCl	3.21	very strongly acid	3.49	strongly acid	4.09	strongly acid	5.95	slighly acid
Cation exchange capacity T	37.3	very low	30.40	very low	27.60	very low	31.50	very low
Content of exchangeable basic Cations S	13.5	very low	17.30	very low	21.80	very low	29.30	low
Base saturation V	36.30	low saturated	56.80	moderately saturated	78.90	very highly saturated	93.20	highly saturated
Soil chemistry								
C_{ox}	3.43	very high content of humic compounds	0.93	low content of humic compounds	0.55	high content of humic compounds	0.83	low content of humic compounds
N_t	0.187	moderate	0.053	low	0.062	moderate	0.069	moderate
C:N	18.3	–	17.5	–	8.9	–	12.0	–

Table 3. Properties of particular soil horizons, study plot No. 4, Rudice, universal whelled tractor Zetor 7245

No. of forest stand: 146A7; District in Masaryk Forest Křtiny: Habrůvka; Hauling machine: UWT; Pedogenetic substrate: polygenetical loams mixed with flintstones; Soil group: Luvisol; Soil subunit: Dystic; Code: dyLV

Horizont	Ah	Designation of a property	Eh	Designation of a property	El	Designation of a property	EB	Designation of a property	Bt	Designation of a property
Soil physics										
2–0.25	7.52		10.09		15.05		9.26		7.50	
0.25–0.1	5.18		8.24		9.38		6.80		6.23	
0.1–0.05	17.18	loam	13.51	loam	14.21	loam	13.06	clay loam	24.87	clay
0.05–0.01	29.92		28.92		25.96		18.20		7.80	
0.01–0.002	19.24		18.56		16.96		13.68		12.76	
pod 0.002	20.96		20.68		18.44		39.00		40.84	
Maximum capillary capacity Θ_{MKK}	26.70	waterholding	28.88	waterholding	27.31	waterholding	33.20	strongly waterholding	33.39	strongly waterholding
Moisture content by mass w	16.33	moderately wet	14.93	fairly moist	14.49	fairly moist	18.49	fairly moist	17.12	fairly moist
Wet bulk density ρ_w	1.24	–	1.43	–	1.71	–	1.87	–	1.87	–
Bulk density ρ_d	1.07	–	1.24	–	1.49	–	1.57	–	1.60	–
Density ρ_s	2.39	–	2.44	–	2.56	–	2.73	–	2.89	–
Porosity P	55.45	high	49.10	moderate	41.67	low	42.38	low	44.63	low
Moisture content by volume Θ	17.40	–	18.58	–	21.61	–	29.10	–	27.39	–
Soil aeration A	38.05	–	30.52	–	20.06	–	13.28	–	17.24	–
Minimal air capacity A_{MKK}	28.75	highly aerated	20.22	highly aerated	14.36	moderately aerated	9.18	low aerated	11.24	highly aerated
Relative soil moisture R_V	65.17	–	64.34	–	79.13	–	87.65	–	82.03	–
Relative saturation R_{NP}	31.38	–	37.84	–	51.85	–	68.66	–	61.37	–
Soil physicochemistry										
pH/H_2O	3.92	strongly acid	4.26	moderatedly adic	4.22	moderatedly adic	4.75	moderatedly adic	5.13	slighly acid
pH/KCl	3.33	very strongly acid	3.60	strongly acid	3.81	strongly acid	3.98	strongly acid	4.21	strongly acid
Cation exchange capacity T	27.4	very low	19.60	very low	18.50	very low	14.90	very low	15.20	very low
Content of exchangeable basic cations S	2.60	very low	3.90	very low	6.40	very low	6.60	very low	10.10	very low
Base saturation V	9.60	highly unsaturated	20.00	unsaturated	34.50	low saturated	44.01	low saturated	66.50	moderately saturated
Soil chemistry										
C_{ox}	4.4	very high content of humic compounds	2.2	high content of humic compounds	1.68	high content of humic compounds	0.80	low content of humic compounds	1.18	high content of humic compounds
N_t	0.26	high	0.099	moderate	0.099	moderate	0.093	moderate	0.093	moderate
C:N	16.9	–	22.2	–	17.0	–	8.6	–	12.7	–

Table 4. The changes in soil physical parameters after the travel of the universal wheeled tractor, study plot No. 2, Babice nad Svitav ou, the topsoil (7–60 cm)

	Month of the field investigation	Soil horizon	Density (g·cm^{-3})	Wet bulk density (g·cm^{-3})	Bulk density (g·cm^{-3})	Maximum capillary capacity (%)	Porosity (%)	Moisture content by volume (%)	Moisture content by mass (%)	Soil aeration (%)	Minimal air capacity (%)	Relative soil moisture (%)	Relative saturation (%)
Study plot (effect of a travel)	October 07		2.24	0.94	0.74	25.97	67.15	20.07	27.25	47.08	41.18	77.28	29.89
	April 08	Ah	2.55	1.62	1.27	42.54	50.41	35.45	28.02	14.96	7.87	83.33	70.33
	October 08		2.56	1.96	1.59	37.37	37.85	22.74	36.23	1.62	0.48	96.95	95.71
Control plot	October 07		2.24	0.94	0.74	25.97	67.15	20.07	27.25	47.08	41.18	77.28	29.89
	April 08	Ah	2.55	1.54	1.18	40.91	53.59	35.70	30.15	17.89	12.68	87.26	66.62
	October 08		2.55	1.58	1.22	41.86	52.16	29.79	36.36	15.80	10.30	86.86	69.71
Study plot (effect of a travel)	October 07		2.59	1.53	1.30	30.74	49.72	22.24	17.07	27.48	18.98	72.35	44.73
	April 08	El	2.65	1.81	1.49	38.13	43.56	31.49	21.09	12.07	5.43	82.59	72.28
	October 08		2.56	1.83	1.48	38.88	42.10	23.48	34.86	7.24	3.22	89.66	82.81
Control plot	October 07		2.59	1.53	1.30	30.74	49.72	22.24	17.07	27.48	18.98	72.35	44.73
	April 08	El	2.56	1.71	1.35	40.93	47.31	35.91	26.58	11.40	6.38	87.74	75.9
	October 08		2.58	1.82	1.47	38.72	42.81	23.5	34.64	8.17	4.09	89.46	80.92
Study plot (effect of a travel)	October 07		2.79	1.87	1.54	36.74	44.67	32.44	21.05	12.23	7.93	88.30	72.63
	April 08	Bt	2.59	1.88	1.56	35.11	39.92	32.04	20.58	7.88	4.81	91.26	80.26
	October 08		2.54	1.84	1.46	40.06	42.48	26.04	38.01	4.470	2.42	94.88	89.48
Control plot	October 07		2.79	1.87	1.54	36.74	44.67	32.44	21.05	12.23	7.93	88.30	72.63
	April 08	Bt	2.51	1.84	1.49	39.24	40.87	35.29	23.75	5.58	1.63	89.93	86.35
	October 08		2.58	1.92	1.58	36.78	38.64	21.65	34.23	4.41	1.86	93.07	88.58

deals also wite potential influences of the actual weather course). For the individual study plots, the influence of the changed soil structure is very well manifested in the values of saturated conductivity as well as in the compaction of upper soil horizons.

Study plot No. 1, Babice nad Svitavou, lies in the top part of a ridge, where an exceptionally high skeleton content is typical within the soil profile. Due to this fact, it was not possible to use the Guelph permeameter – the skeleton would distort the respective measurement to such an extent that the obtained results would be absolutely misleading. For this reason, the authors inevitably regarded the high skeleton content as a factor making the survey on this study plot impossible. However, the authors are aware of the fact that from the forestry aspect, skeleton is quite beneficial, as the stones that are in mutual contact show much higher bearing capacity and also reinforce the soil profile: in sharp-edged skeleton, the stones are strongly engaged and work as the so-called railway superstructure; therefore, forestry mechanization does not cause any high compaction of upper soil horizons there. The locality is on a terrain elevation passing to a slope of

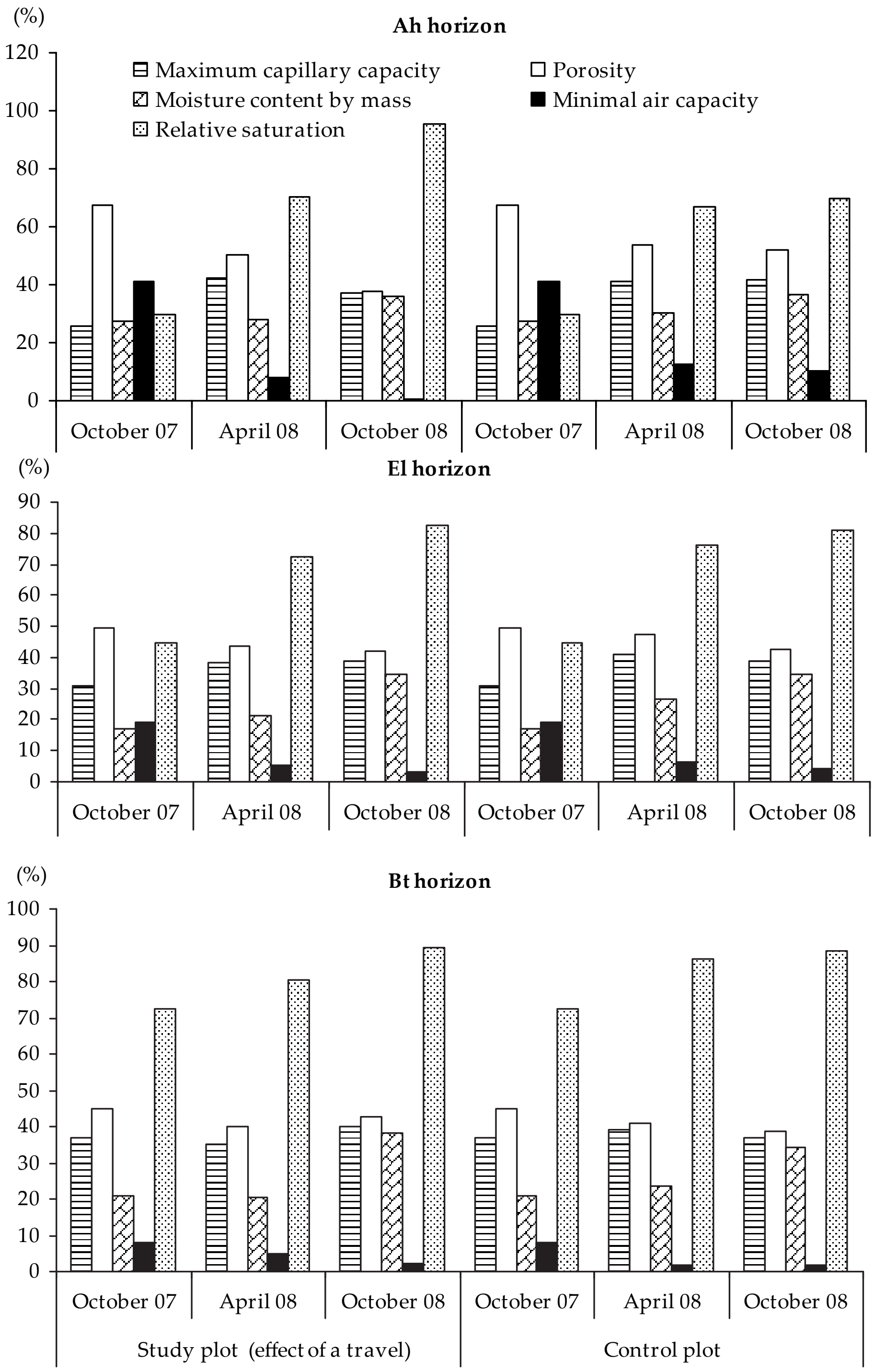

Fig. 1. The results of the laboratory analyses, the metal cylinders, study plot No. 2, Babice nad Svitavou, UWT

Table 5. The changes in soil physical parameters after the travel of the harvestor PONSSE ERGO 16 and the forwarder Gremo 950, study plot No. 3, Rudice, the topsoil (4–55 cm)

	Month of the field investigation	Soil horizon	Density ($g \cdot cm^{-3}$)	Wet bulk density ($g \cdot cm^{-3}$)	Bulk density ($g \cdot cm^{-3}$)	Maximum capillary capacity (%)	Porosity (%)	Moisture content by volume (%)	Moisture content by mass (%)	Soil aeration (%)	Minimal air capacity (%)	Relative soil moisture (%)	Relative saturation (%)
Study plot (effect of a travel)	October 07		2.42	1.30	1.16	25.68	52.23	14.78	12.78	37.45	26.55	57.55	28.30
	April 08	A	2.50	1.51	1.13	41.98	54.87	38.49	34.11	16.38	12.89	91.69	70.15
	October 08		2.56	1.77	1.54	38.00	39.93	15.11	23.21	16.72	1.93	61.08	58.12
Control plot	October 07		2.42	1.30	1.16	25.68	52.23	14.78	12.78	37.45	26.55	57.55	28.30
	April 08	A	2.45	1.66	1.24	44.00	49.39	42.18	34.00	7.21	5.39	95.86	85.41
	October 08		2.56	1.45	1.30	33.32	49.42	11.54	14.96	34.46	16.10	44.90	30.27
Study plot (effect of a travel)	October 07		2.59	1.44	1.27	28.90	50.80	16.40	12.87	34.40	21.9	56.75	32.28
	April 08	El	2.62	1.72	1.43	33.55	45.27	28.77	20.08	16.50	11.72	85.75	63.56
	October 08		2.58	1.75	1.50	36.28	41.79	16.9	25.36	16.43	5.51	69.90	60.68
Control plot	October 07		2.59	1.44	1.27	28.90	50.80	16.40	12.87	34.40	21.90	56.75	32.28
	April 08	El	2.60	1.93	1.62	34.11	37.80	31.59	19.55	6.21	3.69	92.61	83.58
	October 08		2.63	1.42	1.30	33.14	50.66	9.40	12.20	38.46	17.52	36.81	24.08
Study plot (effect of a travel)	October 07		2.65	1.92	1.62	34.49	38.85	29.79	18.37	9.06	4.36	86.37	76.68
	April 08	EB	2.65	1.91	1.62	31.57	38.59	28.12	17.31	10.47	7.02	89.07	72.87
	October 08		2.62	2.03	1.70	33.12	35.03	19.51	33.18	1.85	1.91	100.18	94.72
Control plot	October 07		2.65	1.92	1.62	34.49	38.85	29.79	18.37	9.06	4.36	86.37	76.68
	April 08	EB	2.65	1.92	1.65	30.64	37.55	27.20	16.46	10.35	6.91	88.77	72.44
	October 08		2.60	1.88	1.63	36.18	37.30	15.43	25.19	12.11	1.12	69.62	67.54

north-northeast exposition, slope gradient to 10°. On this plot, the planned measurement was not possible due to the high skeleton content which did not allow the collection of physical cylinders from the required depths of the soil profile or boring of a test hole with intact walls. Nevertheless, such conditions are common in forestry and therefore they should be included in the debate about possible damage caused by wheel traffic. Due to this fact they were not excluded from the evaluation and they are also paid attention in the Discussion section. In terms of the texture, from the surface horizon they can be classified as sandy silt loam (lighter medium) with decreasing tendency to silty clay (very heavy) in Bt horizon. Porosity and aeration decrease with depth, the whole profile is freshly moist. Active soil reaction changes towards the Bt horizon from moderately acidic to neutral with a simultaneous increase in the maximum sorption capacity and base saturation. The surface is very humic with very high nitrogen content and favourable C:N ratio around the value of 17–18.

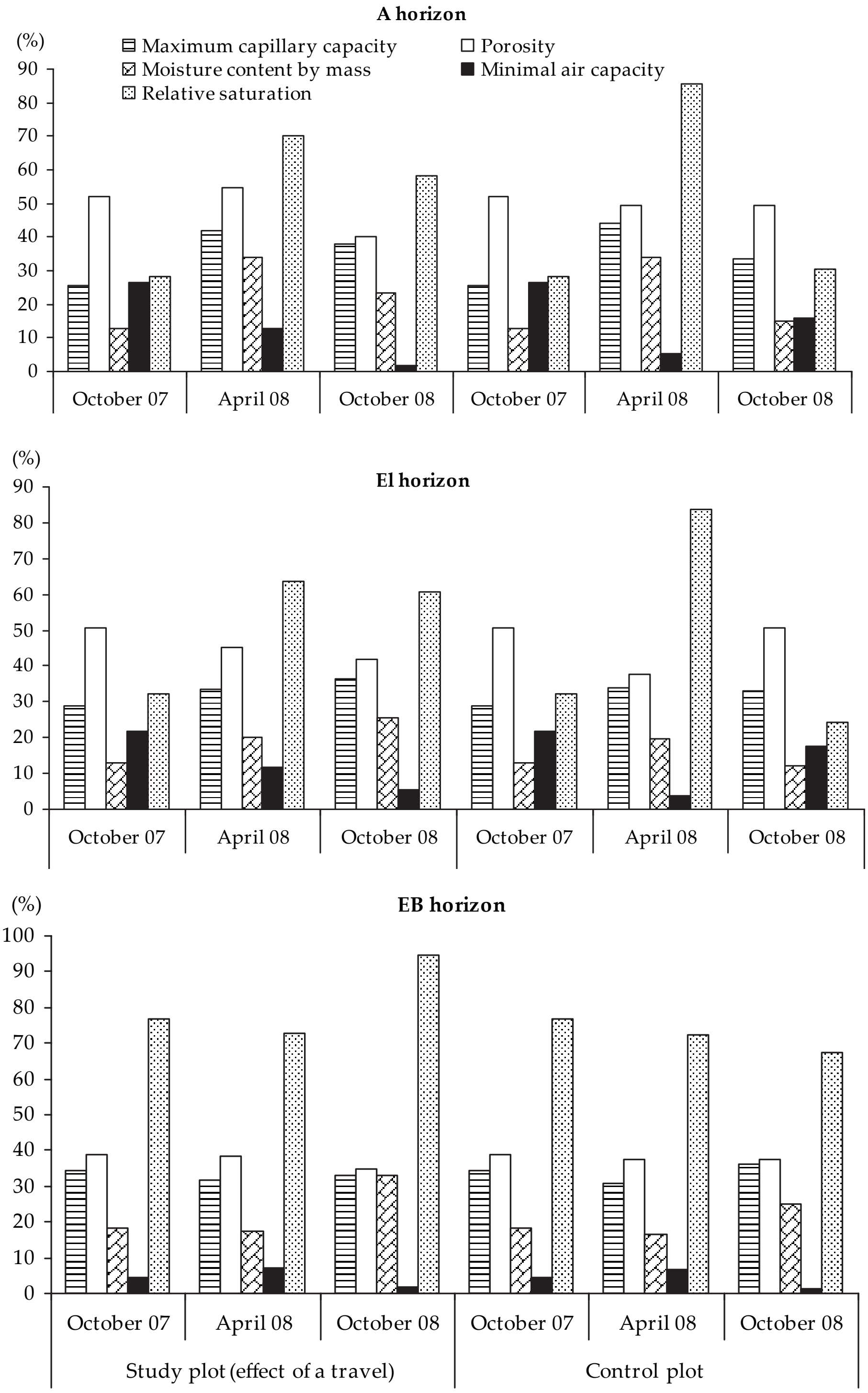

Fig. 2. The results of the laboratory analyses, the metal cylinders, study plot No. 3, Rudice, the harvestor PONSSE ERGO 16 and the forwarder Gremo 950

Table 6. The changes in soil physical parameters after the travel of the universal wheeled tractor, study plot No. 4, Rudice, the topsoil (5–35 cm)

	Month of the field investigation	Soil horizon	Density ($g \cdot cm^{-3}$)	Wet bulk density ($g \cdot cm^{-3}$)	Bulk density ($g \cdot cm^{-3}$)	Maximum capillary capacity (%)	Porosity (%)	Moisture content by volume (%)	Moisture content by mass (%)	Soil aeration (%)	Minimal air capacity (%)	Relative soil moisture (%)	Relative saturation (%)
Study plot (effect of a travel)	October 07		2.39	1.24	1.07	26.70	55.45	17.40	16.33	38.05	28.75	65.17	31.38
	April 08	Ah	2.55	1.84	1.56	32.83	38.98	28.44	18.27	10.54	6.15	86.63	72.97
	October 08		2.62	1.89	1.63	29.16	37.68	16.08	26.23	11.45	8.52	89.95	69.60
Contro+l plot	October 07		2.39	1.24	1.07	26.7	55.45	17.40	16.33	38.05	28.75	65.17	31.38
	April 08	Ah	2.60	1.71	1.41	33.83	45.74	29.37	20.79	16.37	11.91	86.82	64.21
	October 08		2.58	1.42	1.27	35.62	50.72	12.16	15.45	35.27	15.10	43.37	30.46
Study plot (effect of a travel)	October 07		2.44	1.43	1.24	28.88	49.10	18.58	14.93	30.52	20.22	64.34	37.84
	April 08	Eh	2.65	1.79	1.55	27.61	41.43	24.05	15.52	17.38	13.82	87.11	58.05
	October 08		2.62	1.87	1.59	36.90	39.37	17.99	28.55	10.82	2.47	77.37	72.52
Control plot	October 07		2.44	1.43	1.24	28.88	49.10	18.58	14.93	30.52	20.22	64.34	37.84
	April 08	Eh	2.66	1.88	1.54	37.05	42.13	33.60	21.83	8.53	5.08	90.69	79.75
	October 08		2.59	1.50	1.33	35.88	48.67	12.70	16.89	31.78	12.79	47.07	34.70
Study plot (effect of a travel)	October 07		2.56	1.71	1.49	27.31	41.67	21.61	14.49	20.06	14.36	79.13	51.85
	April 08	El	2.60	1.85	1.62	25.84	37.97	23.88	14.78	14.09	12.13	92.41	62.89
	October 08		2.62	1.86	1.58	36.34	39.48	17.13	27.13	12.35	3.14	74.66	68.71
Control plot	October 07		2.56	1.71	1.49	27.31	41.67	21.61	14.49	20.06	14.36	79.13	51.85
	April 08	El	2.67	2.03	1.74	33.59	34.95	28.78	16.55	6.17	1.36	85.68	82.34
	October 08		2.63	1.66	1.48	30.31	43.83	12.55	18.55	25.28	13.52	61.20	42.32

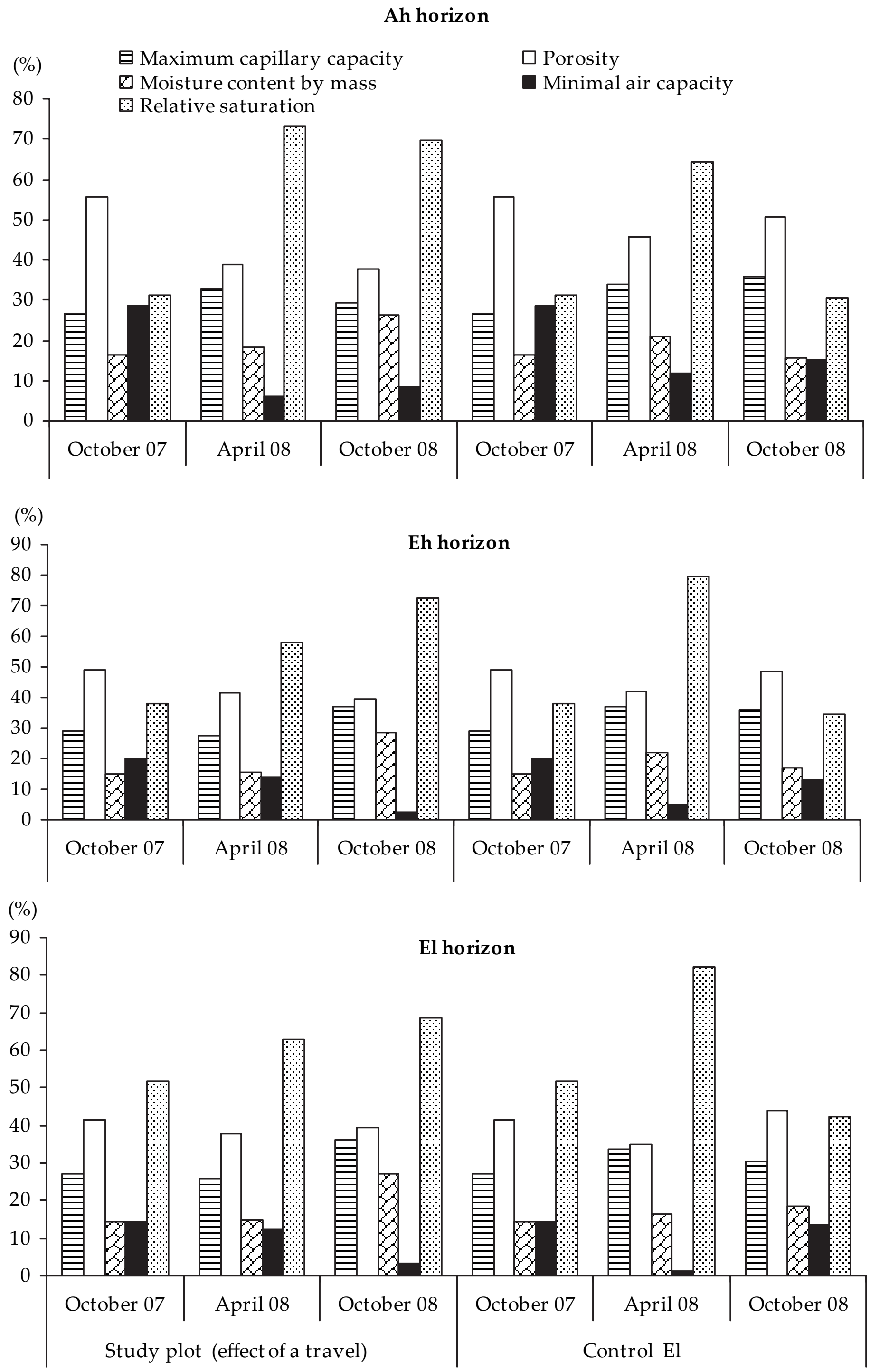

Fig. 3. The results of the laboratory analyses, the metal cylinders, study plot No. 4, Rudice, UWT

Study plot No. 2, Babice nad Svitavou, was used as a study plot for the evaluation of traffic of a universal wheeled tractor during skidding of harvested timber. The presented laboratory analyses confirm negative changes of physical, hydrophysical and soil-mechanical properties after wheel traffic above the level of seasonal dynamics of soil properties; the difference in the values measured at different times decreases with depth. The bulk density increased in the upper Ah horizon from the original 0.74 g·cm^{-3} prior to the operation to 1.27 g·cm^{-3} after the operation and further up to 1.59 g·cm^{-3} measured after further six months. Simultaneously, the porosity decreased from 67% to the final 38% and aeration of the horizon even from 47% to the critical 1.6%. In El horizon, the changes were not so marked, however, the trend that the values do not improve even after 6 months from the operation has been observed there as well. The bulk density showed a change from 1.30 g·cm^{-3} to 1.48 g·cm^{-3} for two successive measurements, the porosity decreased from 50% to 42%. The decrease in aeration does not stop after wheel traffic, but continues gradually in the series 27–12–7%. In Bt horizon, the impact of machinery traffic is almost undetectable, only the changes corresponding to seasonal dynamics of soil properties have been observed. For the purpose of evaluation it is possible to prove that the changes in volume weights due to compaction lead to values limiting the tree root growth, however, in the subsurface Bt horizon, measurements detected the limit values already before the machinery operation. The bulk density only approximates the critical values according to LHOTSKÝ (2000); on the other hand, aeration strongly exceeds the limit level of 10% in all horizons.

The subsection Field surveys contains a description of the impacts of forestry mechanization traffic (5 passes of the universal wheeled tractor Zetor 7245 Horal transporting 12 m^3 of timber in semi-suspension; control measurements performed 15 m from the testing trail). The variance of values of field saturated hydraulic conductivity Kfs (Fig. 4a and 4b) was by two orders of magnitude: from 1.6×10^{-5} $m \cdot s^{-1}$ up to 0.03×10^{-5} $m \cdot s^{-1}$. After operation of the universal wheeled tractor Zetor 7245 on the study plots at the Babice nad Svitavou locality, partial improvement by one order was observed, i.e. in the case of the lowest measured initial values to 0.3×10^{-5} $m \cdot s^{-1}$. The results of the tests have clearly proved that the compaction of soil (Fig. 6) occurs, since the control measurements keep always the same angle of decrease in all three measurements (before the operation, after the operation and six months from the machinery operation). Compaction of soil is evident since with the same number of strokes, only medium depth was reached compared with the control test.

Study plot No. 3, Rudice (characterized in the subsection Field surveys, harvesting and hauling 560 m^3 of timber, a three-axle PONSSE ERGO 16 harvester, a four-axle Gremo 950 forwarder); the

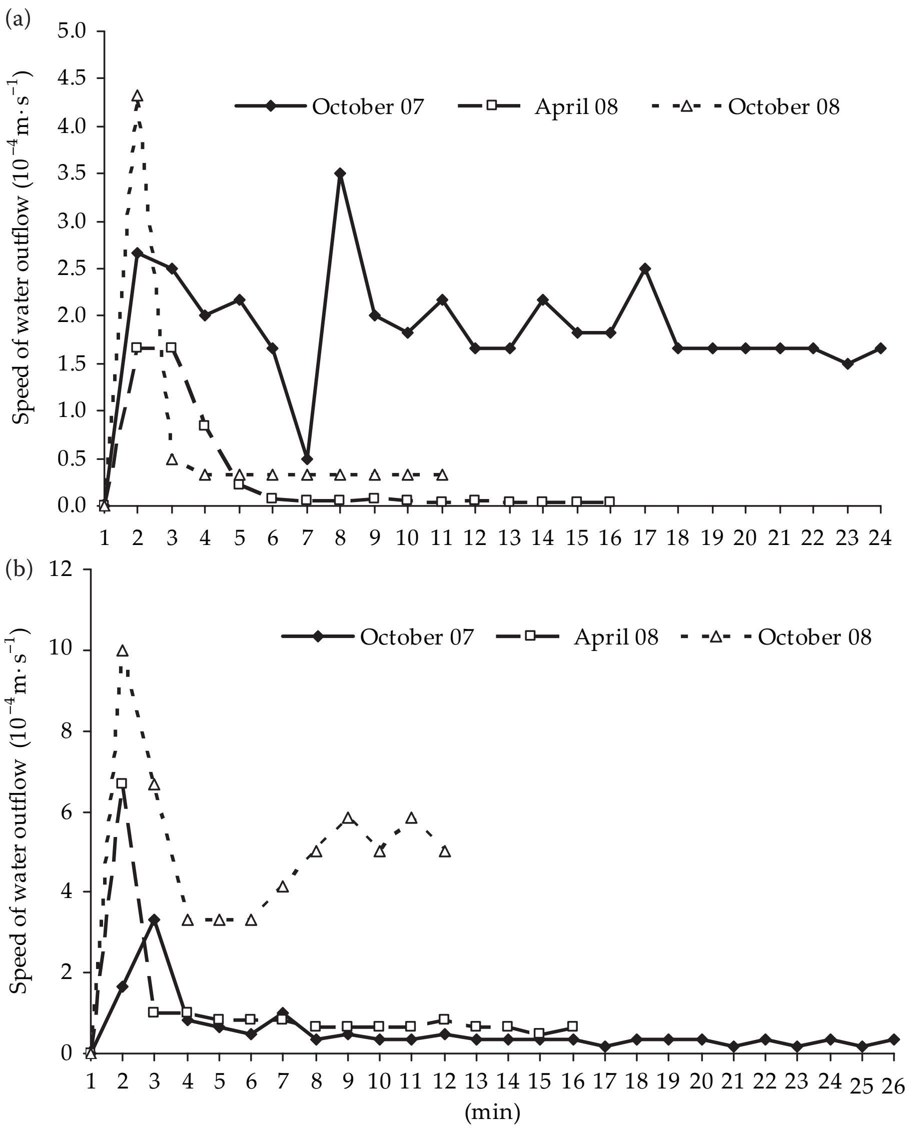

Fig. 4. Flow rate dynamics, study plot No. 2, Babice nad Svitavou, the universal wheeled tractor Zetor 7245 – (a) the travel and (b) the control measurement

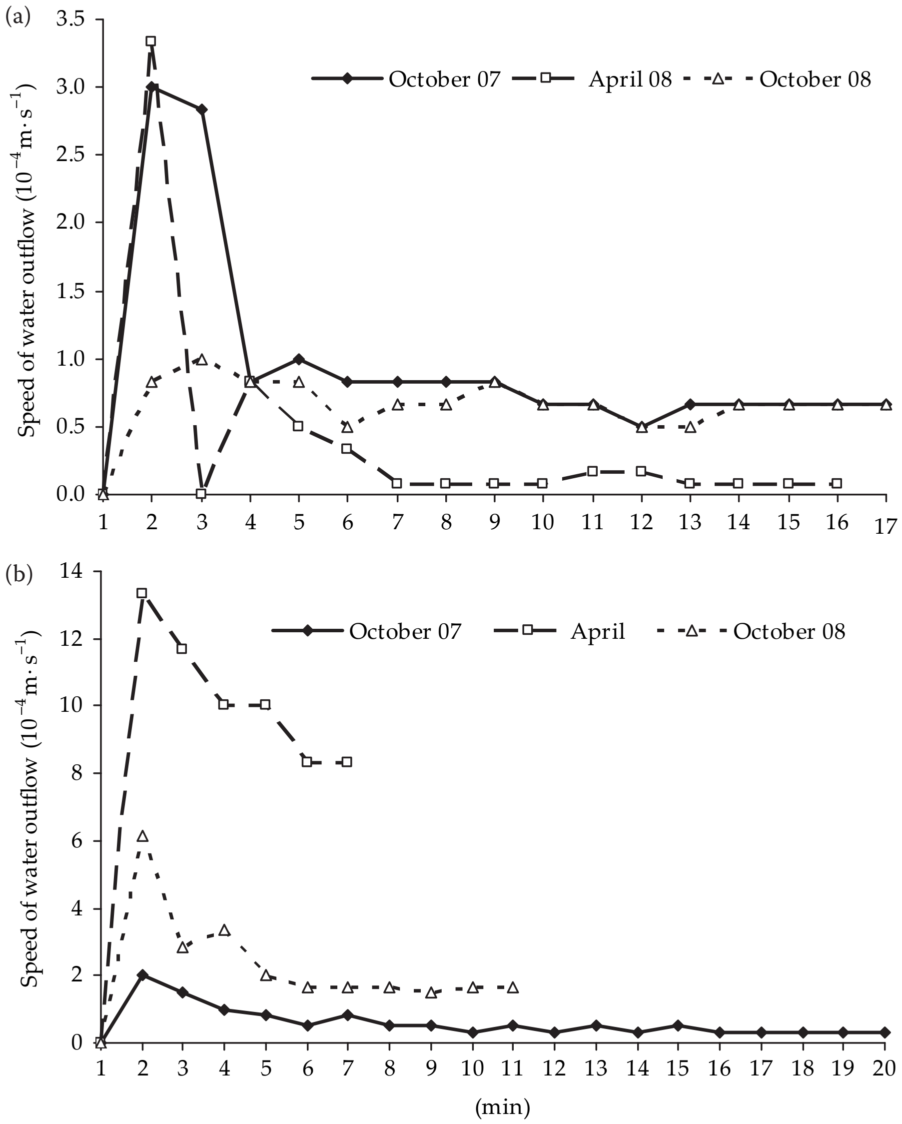

Fig. 5. Flow rate dynamics, study plot No. 3, Rudice, the harvestor PONSES ERGO 16 and forwarder Gremo 950 (a) the travel and (b) the control measurement

performed field (Figs. 5a and 5b) and laboratory measurements proved the phenomenon of soil horizon compaction shortly after wheel traffic. Within six months from the operation, all measurements showed a worsening of the detected negative influence of forestry mechanization operation (including the results of laboratory analyses of the collected uniform metal cylinders). Marked negative impacts of forestry mechanization traffic were proved in physical, hydrophysical as well as soil-mechanical properties: bulk density in A horizon increased from 1.16 to 1.30 and 1.54 $g\cdot cm^{-3}$, in El horizon from 1.27 to 1.43 and 1.50 $g\cdot cm^{-3}$ and in EB horizon the values oscillated again around 1.65 $g\cdot cm^{-3}$ without direct connection with machinery traffic. The porosity decreased gradually from 52% to 40% in A horizon, from 51% to 42% in El horizon and a slight decrease from the original 39% to 35% was observed also in EB horizon. Aeration showed a change in the first two horizons that remained the same throughout the time. In A horizon, this decrease was from 37% to 17% and in El horizon from 34% to 16%. In EB horizon, porosity improved from 9% to 10.5% measured after the operation, however, after six months a rapid drop to 2% occurred, which is markedly below the minimum aeration limit. From the viewpoint of evaluation we can say that the volume weight of the upper soil horizons is near the level of root growth restriction, in EB horizon the limit is exceeded by all of the measured values. Porosity reaches the critical values only in measurements after six months, in the case of EB horizon in all values. Bulk density, just like the previously described properties, shows the limit values of the subsurface horizon EB, even before the operation.

Study plot No. 4, Rudice (characterized in the subsection Field surveys, skidding of 16.4 m^3 of raw wood by a universal wheeled tractor Zetor 7245 with forestry body) showed the strong compaction of upper soil horizons both immediately after the operation and within six-month time, which is fully documented by the results of control measurements (Figs. 6a and 6b). The skidding operation of the tractor had a negative effect on surface organomineral horizons in terms of their physical, hydrophysical and soil-mechanical properties; in El horizon, these values tend to restore the original properties to the state prior to the operation. In Ah horizon, the bulk density gradually increased from 1.07 g·cm^{-3} to 1.63 g·cm^{-3}, porosity decreased from 55% to 38% and aeration from 38% to 11%. In Eh horizon, the intensity of changes was smaller, the bulk density rose from 1.24 g·cm^{-3} to 1.59 g·cm^{-3}, porosity decreased from 49% to 39% and aeration dropped from 31% to 11%. In El horizon, the bulk density increased from 1.49 g·cm^{-3} to 1.62 g·cm^{-3} and then improved again to the value of 1.58 g·cm^{-3}. Porosity decreased from 42% to 38%; as mentioned above, after six months, the tendency to resume the original values was observed (40%). Aeration decreased in the series 20–14–12%. The El horizon showed critical values of volume weight for root growth in all measurements; such values were also present in the remaining horizons during both measurements after the operation. The values of aeration for this locality did not exceed the limits for plant root growth restriction in any horizon. The control test after the operation and after six months proved that the trend did not potentially influence the site due to stochastic manifestation or abiotic factors.

For study plot No. 2 we can generally conclude that the negative impact of the operation reaches the depth of 40 cm, i.e. a half of the genetic depth of the specific soil. The repeated measurements revealed that the soil profile compaction tended to decrease with time. For study plots No. 3 and 4 we can state that decreases in the values of field saturated hydraulic conductivity Kfs by one order of

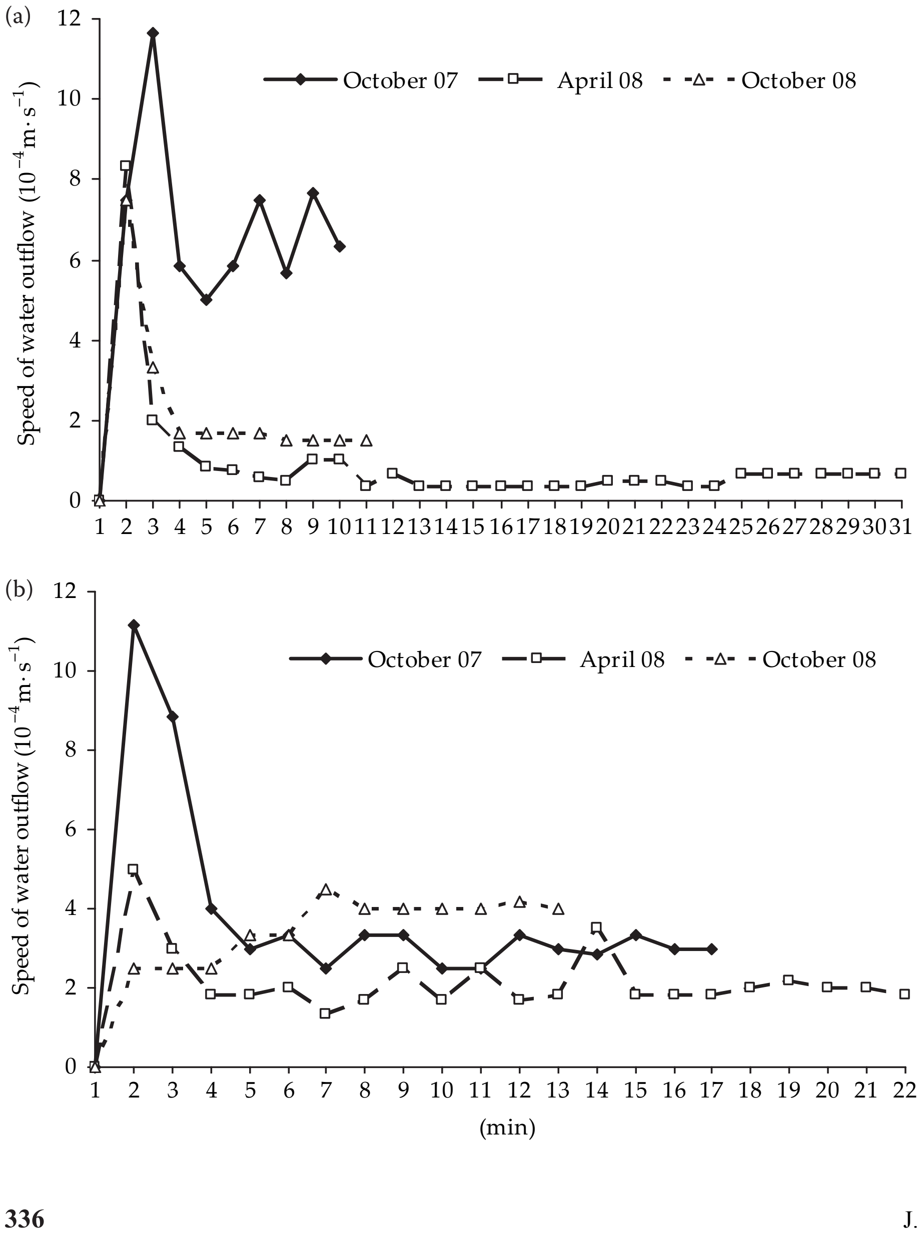

Fig. 6. Flow rate dynamics, study plot No. 4, Rudice, the universal wheeled tractor Zetor 7245 – (a) the travel and (b) the contral measurement

Table 7. Field-saturated hydraulic conductivity 10^{-5} Kfs ($m.s^{-1}$)

Study plot	Study plot (effect of a travel)			Control plot		
	October 07	April 08	October 08	October 07	April 08	October 08
No. 2 – Babice	1.669	0.034	0.342	0.256	0.642	5.565
No. 3 – Rudice	0.684	0.085	0.684	0.342	8.561	0.171
No. 4 – Rudice	6.849	0.684	1.541	3.082	1.969	4.152

magnitude were measured, namely at locality No. 3 from 0.7×10^{-5} $m \cdot s^{-1}$ to 0.09×10^{-5} $m \cdot s^{-1}$ and at locality No. 4 from 6.9×10^{-5} $m \cdot s^{-1}$ to 0.7×10^{-5} $m \cdot s^{-1}$. After the operation of the universal wheeled tractor Zetor 7245 in Rudice, the value of field saturated hydraulic capacity rose to 1.5×10^{-5} $m \cdot s^{-1}$. Six months after the operation of PONSSE ERGO 16 harvester and Gremo 950 forwarder at study plot 3 in Rudice, the saturated hydraulic conductivity returned to the original value. Monitoring of the same characteristic on the control plots revealed an increase of Kfs in the period from October to April, which allows us to conclude that the seasonal changes of the soil profile did not cause any increase of the values of saturated hydraulic conductivity in forestry mechanization ruts (Table 7). Generally we can state that study plots No. 3 and 4 in Rudice show higher values of field saturated hydraulic conductivity. Based on the repeated measurements within six months, the conductivity on both study plots shows that the original values were continually resumed more easily than on the other study plots.

DISCUSSION

As regards the comparability of the field and laboratory tests, it should be stressed that the results of the soil saturated hydraulic conductivity measurements with the Guelph permeameter, used on the same study plots at the same time under the same external conditions, correspond with the results of laboratory measurements of physical and hydrophysical properties – application of the standard gravimetric evaluation with uniform metal cylinders, taken from the individual soil horizons of the examined soil profiles. Identical interpretations of the results of both the field soil-mechanical tests and the laboratory physical and hydrophysical gravimetric analyses support the general recommendation of the authors that further experiments on soils under forest stands should follow the presented study.

From the forestry aspect, discussion on the applicability of the obtained results should be aimed at the problem of variability in the actual course of weather (Lhotský 2000; Ulrich et al. 2003). First of all, mainly the low air temperature (generating the change of water state) and variable weight moisture of the upper soil horizons have some natural impacts on the set of physical, hydrophysical and soil-mechanical properties. As regards the results presented in this study, the authors were aware of the described facts, therefore, they used a high number of measuring points on the monitored study plots with the focus on a possibility of generalization. In general, the authors are clearly aware that climatic factors remain a significant fact regarding the informative value of the application of Guelph permeameter. During the measurements with Guelph permeameter, full saturation does not occur because some air is trapped in a part of the porous system; this space does not contribute to the final conductivity value. According to Kutílek et al. (2000), repeated measurements have shown that the obtained values are realistic and do not require any subsequent correction.

As regards the applicability of the field and laboratory analyses, we can discuss the confirmation or refutation of the hypothesis that the traffic of forestry mechanization during timber hauling has a negative impact on physical, hydrophysical and soil-mechanical properties of soils. From the aspect of laboratory analyses, the authors paid special attention to the evaluation of physical properties, where a short response to the applied pressures is ensured. On the study plots of Babice nad Svitavou locality on the limestone subsoil, a negative shift of the values of all properties occurred immediately after the operation in the first two monitored horizons; these changes were evident even 6 months after the operation itself. Aeration and volume weight reached critical values. It can be stated that six months after the traffic of a universal wheeled tractor, the soil characteristics kept decreasing, without any marks of beginning restoration of the original state before the operations. Harvester technologies of raw timber haulage on study plots outside the karst area (study plots No. 3 and 4, Rudice) also produced negative impacts of the traffic on the measured properties, but with smaller differences compared to control measurements; the impact on the subsurface EB horizon was minimal. The aeration in all horizons measured after the operation of the universal wheeled tractor on the study plot outside the karst was above the critical value limiting the root growth; on the other hand, the volume weight in most measurements after the machinery traffic reached the limit values evidently restricting the growth of roots. As regards the applicability of the presented results, it is apparent that the strongest impact of the universal wheeled tractor operation without signs of remedy was found on forest soil in the karst area. The cause probably lies in the hauling technology used. Specifically from the aspect of the produced locomotion pressures, the hauling tractors used at locality No. 3, Rudice, cause lower impacts as they transport timber from the stand to the loading point and collect the load continuously. Regarding the applicability of the obtained results it should be stated that different tree species compositions on the study plots were manifested rather in the chemical and physicochemical properties of soils at the individual localities than in the assessed physical, hydrophysical and soil-mechanical properties.

CONCLUSION

Changes caused by machinery traffic as well as by climatic and other factors were detected during the measurements of soil conductivity Kfs. In the measurement points affected by machinery operations, the impact of the changed soil structure on the values of saturated conductivity is very well noticeable.

On study plots No. 3 and 4, the values decreased by one order of magnitude: from 0.7×10^{-5} m·s^{-1} to 0.09×10^{-5} m·s^{-1} on study plot No. 3 and from 6.9×10^{-5} m·s^{-1} to 0.7×10^{-5} m·s^{-1} on study plot No. 4; on study plot No. 2 even by two orders, i.e. from 1.6×10^{-5} m·s^{-1} to 0.03×10^{-5} m·s^{-1}. After the operation of a universal wheeled tractor at the Babice nad Svitavou locality, the situation partially improved by one order to 0.3×10^{-5} m·s^{-1}, similarly like at the Rudice locality to 1.5×10^{-5} m·s^{-1}. Six months after the use of a harvester and forwarder at the Rudice locality, the saturated hydraulic conductivity returned to its original value.

Monitoring of the same characteristic on control plots documented an increase of Kfs, indicating that the seasonal changes in the soil profile did not cause any rise of the measured values of saturated hydraulic conductivity in the ruts after mechanization operation.

Thus, it is possible to state that study plots No. 3 and 4 at the locality Rudice show higher values of the field saturated hydraulic conductivity, which corresponds to the non-karst soil-forming process: conductivity returns to its original values more easily in these soils.

We can make a general conclusion that through the selected physical properties of the soils measured at three different time periods in the places affected by machinery operation and in unaffected (control) places, we have obtained data enabling us to assess the impact of universal wheeled tractor and harvester technologies on soil during timber hauling from a harvested forest. Beech stands in the karst area and a spruce stand outside the karst were chosen for the universal wheeled tractor while the harvester technologies were used on a study plot outside the karst area only. Open soil profiles and their descriptions together with laboratory analyses of physical, physico-chemical and chemical properties were used for detailed description of the soil conditions at the individual localities. The dynamics of physical and hydrophysical properties was determined by the analyses of undisturbed samples, i.e. samples with the unchanged macrostructural features, taken by uniform metal cylinders 100 cm^3 in volume. Saturated hydraulic conductivity of forest soils was measured directly in the field within six months after the forest machinery operations.

Results of the measurements have proved negative changes of all monitored soil properties. After a relatively short period of 6 months after the machinery traffic, further changes were observed with tendencies either towards restoration of the original state or towards further worsening. The magnitudes of pressures affecting the soil decrease with depth, together with differences in the changes of physical properties. The critical values from the aspect of vegetation growth were exceeded mainly in the subsurface horizons; however, these properties were closer to the limits already before the machinery operation there. Field saturated hydraulic conductivity indicates also a decrease in the volume of pores after the machinery traffic, with noticeable tendencies to restore the original condition detected as soon as after six months.

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