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Comparison of the physical properties of soils belonging to different reference soil groups

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Abstract: Soil properties can be influenced by long-term agricultural management practices as described in pedological literature. In this study, selected physical properties (particle density and bulk density, total porosity, maximum capillary water capacity, minimum air capacity, field capacity, permanent wilting point and available water capacity) of topsoils from different reference soil groups (Cambisols, Luvisols, Fluvisols, Chernozems and Phaeozems, Leptosols, Stagnosols and Gleysols) were sampled and analysed in the years 2016–2017. The topsoil samples were taken from points of so-called S (specific) soil pits to be sampled from the General Soil Survey of Agricultural Soils (GSSAS) which was accomplished in the years 1961–1970. In addition, some of the properties were also compared with those measured during the GSSAS. Recognising the properties, only the particle density, the maximum capillary water capacity, the permanent wilting point and the available water capacity of the topsoil of the individual soil groups were statistically significantly ($P < 0.05$) different. A comparison of the physical properties with those analysed after more than 40 years was performed, the bulk density increased and the total porosity decreased in the topsoil of the major part of the studied soil groups.

Keywords: comparison study; hydrolimits; soil survey; soil texture

Intensive agricultural management practices can modify different soil properties. Different long-term studies (soil properties are evaluated after more than nine years of different agricultural management practices) have proven the effect of agricultural management practices on the soil organic carbon, total nitrogen, pH, cation exchange capacity, potentially mineralisable N, aggregate stability, bulk density, total porosity, water holding capacity, field capacity, permanent wilting point and other soil properties (Blanco-Canqui et al. 2006; McVay et al. 2006; Filho & Tessier 2009; Van Eerd et al. 2014; Suwara et al. 2016; Irmak et al. 2018; Meng et al. 2019).

The particle density of soil mainly depends on its mineralogical composition and organic matter content; it is used for the calculation of the soil porosity and is supposed to range from 2.6 to 2.7 g/cm^3 (Blanco-Canqui et al. 2006). The bulk density is an indicator of the soil compaction and health and its values depend on the texture, organic matter content, constituent minerals and porosity (Baver et al. 1972; Hanks & Ashcroft 1980; Šimečková et al. 2016). It has an effect on the root development and crop yield and usually increases with the soil depth (Dam et al. 2005; Makovníková et al. 2017). The bulk density is an important conversion of weight-based data to volume (and area) - related data (Brady & Weil 2002). As stated in the work by Carter (1990), the bulk density is influenced by inappropriate land use, heavy agricultural machinery and natural pro-

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cesses. The bulk density can be measured directly (the core method, excavation and clod methods) or indirectly (regression approaches or the radiation method) (Al-Shammary et al. 2018). Both the total soil porosity and bulk density are important indicators of the status of the physical properties of the soil. The total soil porosity is calculated from the bulk density and particle density values or from the saturation moisture content (Hanks & Ashcroft 1980). A detailed description of the pore size distribution is given by Lal and Shukla (2004). The maximum capillary water capacity is the ability of the soil to hold water for the needs of plants and the minimum air capacity is the air content of the soil when it is wetted to its maximum capillary water capacity (Vopravil et al. 2017). The factors that affect the value of the maximum capillary water capacity and the minimum air capacity are described in the works by Šimečková et al. (2016) and Marfo et al. (2019).

The field capacity is the water content at –33 kPa and the permanent wilting point represents the water content estimated at –1 500 kPa (Miller & Donahue 1990). The field capacity and permanent wilting point are influenced by the texture, organic matter content and its quality (Hemmat et al. 2010; Minasny & McBratney 2018). Other factors that influence the field capacity are described in the work by Kirkham (2004). The available water capacity is calculated as the difference between the water content at the field capacity and the permanent wilting point (Huntington 2006).

Long-term intensive agriculture can influence soil properties. It is, therefore, important to obtain information on the status and changes of these soil properties. The information can be used to prevent or improve the negative status of agricultural soils. The aim of this study was to investigate: (a) the particle density of the topsoil of agriculturally utilised soils; (b) the bulk density, the total porosity, the maximum capillary water capacity and the minimum air capacity of the topsoil of agricultural soils in the Czech Republic and their change after more than 40 years; (c) the field capacity, the permanent wilting point and the available water capacity of the topsoil of agricultural soils.

MATERIAL AND METHODS

Selection of soils. To evaluate the changes in the physical soil properties of different reference soil groups (IUSS Working Group WRB 2015), the database from the so-called S (specific) soil pits has been used. They were obtained as a result of the General Soil Survey of Agricultural Soils (GSSAS), which took place in the former Czechoslovakia in the years 1961–1970. In the period of 2016–2017, the points of the original 170 S-soil pits were identified on the basis of the original field location of the soil records. Their original location in map sheets (georeferenced points – GPS positions) was used and these points were verified (tested) in the terrain by drilling using boring bars and on the basis of different criteria (appropriate soil profile stratigraphy, texture of the genetic soil horizons and soil substrate classification). These criteria were further specified (appropriate soil types and subtypes or a possible change corresponding to a short pedogenic development, appropriate classification of the soil to the System of Evaluated Soil Ecological Units, appropriate new formations and coatings). The System of Evaluated Soil Ecological Units is described by Podhrázská et al. (2015). In the period of 2016–2017, the coordinates of all the excavated soil pits were recorded. It was not possible to ensure the same status of the soil environment (soil moisture, temperature, etc.) as in the case of the GSSAS. Several criteria were selected for the S-soil pits recognition: their occurrence in agriculturally utilised blocks and the frequency of the occurrence of the individual soil types.

Measurements. After the excavation of the soil pits (1.2 × 0.8 × 0.7 m), disturbed and undisturbed (using a Kopecky cylinder core with a volume of 100 cm^3) samples were taken from the topsoil and subsoil with three repetitions. Only the samples from the topsoil were analysed and evaluated in this study. The samples from the subsoil will be evaluated in some other studies. The digging of the soil pits, the sampling from the upper two horizons and the analyses of the soil samples were performed using the same methods that were implemented during the GSSAS (Němeček et al. 1967). From 170 S-soil pits, 47 S-soil pits (Cambisols, Luvisols, Fluvisols, Chernozems plus Phaeozems, Leptosols, Stagnosols plus Gleysols) were treated in this study for the assessment of the particle and bulk density, total soil porosity, minimum air capacity and maximum capillary water capacity in the topsoil. The other S-soil pits will be used in some further studies. The bulk density, total soil porosity, minimum air capacity and maximum capillary water capacity of the topsoil of these 47 S-soil pits were also compared with the historical values archived in the

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GSSAS database. The soil types and subtypes were also classified according to Němeček et al. (2001) and the IUSS Working Group WRB (2015). The physical properties of the soils of the same reference soil groups (IUSS Working Group WRB 2015) were expressed as the mean ± standard error and minimum value–maximum value. The particle density was measured according to ISO 11508 (2017). The physical soil properties (bulk density, total soil porosity, minimum air capacity and maximum capillary water capacity) were measured according to Valla et al. (2000). The above-mentioned methods are the same as in the GSSAS. The particle density was measured using a pycnometer. The undisturbed soil samples (in a Kopecky physical cylinder) were weighed after drying at 105 °C to a constant weight; the bulk density was calculated as the dry weight/volume. The total porosity was calculated from the bulk and particle density. The maximum capillary water capacity was obtained after suction of the fully saturated soil samples (for 2 h) and the minimum air capacity was calculated from the total porosity and maximum capillary water capacity. During the GSSAS, Novak's classification of the soil texture was used. The particle-size fractions used in the GSSAS are described by Jandák et al. (2015). In this study, a < 0.002 mm fraction was measured or calculated (from the linear dependence) and the soil textural classes were classified according to the Soil Science Division Staff (2017).

Field capacity, permanent wilting point and available water capacity. The field capacity (FC) and permanent wilting point (PWP) were assessed in the topsoil of 43 S-soil pits (representatives of Cambisols, Luvisols, Fluvisols, Chernozems, Leptosols, Stagnosols plus Gleysols). These obtained values were not the subject of comparison to the mentioned historical data. The FC (–33 kPa) and PWP (–1500 kPa) were used for the calculation of the available water capacity (Haberle & Svoboda 2015).

Statistical analyses. The differences in the values of the particle and bulk density, total soil porosity, minimum air capacity, maximum capillary water capacity, field capacity, permanent wilting point and available water capacity were submitted by testing using a One-way ANOVA and Tukey's HSD test. When the assumptions about the parametric tests were not met, a non-parametric Kruskal-Wallis ANOVA and Kruskal-Wallis Multiple-Comparison Z-Value Test with Bonferroni correction for multiple testing were used.

RESULTS AND DISCUSSION

Particle density. The particle density of the individual samples measured in the years 2016–2017 in the topsoil ranged from 2.54 to 2.86 g/cm^3 (Table 1). The highest average value of the particle density was found in the topsoil of the Leptosols and the lowest in the Stagnosols plus the Gleysols (Figure 1). Sig-

Table 1. The selected physical properties of the topsoil of 47 specific soil pits (minimum–maximum)

Reference soil group	USDA textural classification	PD	BD	P	MAC	MCWC
		(g/cm^3)		(%)		
Cambisols	sandy loam, loam, silty loam	2.54–2.75	1.09–1.70	35.1–58.0	1.3–24.7	26.4–43.0
Luvisols	sandy loam, loam, silty loam, sandy clay loam, silty clay loam	2.55–2.66	1.27–1.58	39.2–51.4	1.2–24.0	21.1–40.8
Fluvisols	sandy loam, loam, silty loam, clay loam	2.56–2.63	1.09–1.63	37.0–58.0	2.7–26.9	31.2–42.1
Chernozems plus Phaeozems	loam, silty loam	2.55–2.66	1.29–1.63	37.6–49.5	3.9–11.9	32.8–39.1
Leptosols	sandy loam, loam, clay loam	2.55–2.86	1.33–1.73	35.0–52.9	5.2–20.9	26.6–39.8
Stagnosols plus Gleysols	silty loam	2.55–2.60	1.27–1.49	42.3–51.2	not calculated	35.1–45.1

PD – particle density; BD – bulk density; P – total porosity; MAC – minimum air capacity; MCWC – maximum capillary water capacity; USDA – U.S. Department of Agriculture; USDA textural classification – classification according to the Soil Science Division Staff (2017)

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nificant ($P < 0.05$) differences between the values of the particle density in the topsoil of the studied soil groups are shown in Figure 1.

The minimum and maximum values of the particle density found during the Basal monitoring of the agricultural soils in the Czech Republic were 1.8 and 2.9 g/cm^3, respectively (Sáňka & Materna 2004). Blanco-Canqui et al. (2006) found a significant effect of long-term management practices on the particle density. The authors measured the particle density before the spring tillage and found a significantly higher particle density in the tilled soil under continuous corn when compared with the soil under continuous corn without tillage. Blanco-Canqui et al. (2006) found that long-term manuring plus zero tillage decreased the particle density in the soil under continuous corn when compared with the soil under continuous corn without manuring and tillage. Jorbenadze et al. (2017) listed a higher average particle density, for example, in the topsoil of Dystric and Eutric Gleysols and Histosols (2.70 g/cm^3) when compared with Rendzic Leptosols (2.50 g/cm^3).

Bulk density, total porosity, maximum capillary water capacity and minimum air capacity. The bulk density of the individual soil samples taken from the topsoil in 2016 and 2017 was in the range of 1.09–1.73 g/cm^3 (Table 1). From the average values of the bulk density shown in Figure 2, it is evident that the highest value was found in the topsoil of the Leptosols and the lowest average values in the topsoil of the Stagnosols and Gleysols, Fluvisols and Luvisols (Figure 2). A statistical analysis showed no significant ($P > 0.05$) differences in the bulk density measured in the different soil groups. After more than 40 years, the average values of the bulk density increased in the Cambisols on average by 5.5%, Chernozems plus Phaeozems by 7.5%, Leptosols by 7.7%, Fluvisols by 15.6%, Stagnosols plus Gleysols by 35.6% and decreased in the case of Luvisols by 4.4%.

The values of the total soil porosity in the individual samples from the topsoil were recognised in the range of 35–58% (Table 1). The highest average total soil porosity was found in the topsoil of the Fluvisols and Stagnosols plus Gleysols and the lowest average total soil porosity was found in the case of the Chernozems plus Phaeozems (Figure 3). It could be stated that from 1961–1970 to 2016–2017, the total soil porosity decreased in the Cambisols on average by 5.0%, Fluvisols by 6.0%, Chernozems plus Phaeozems by 8.5%, Leptosols by 8.7%, Stagnosols plus Gleysols by 18.8% and increased in the Luvisols by 7.1%. No significant ($P > 0.05$) differences between

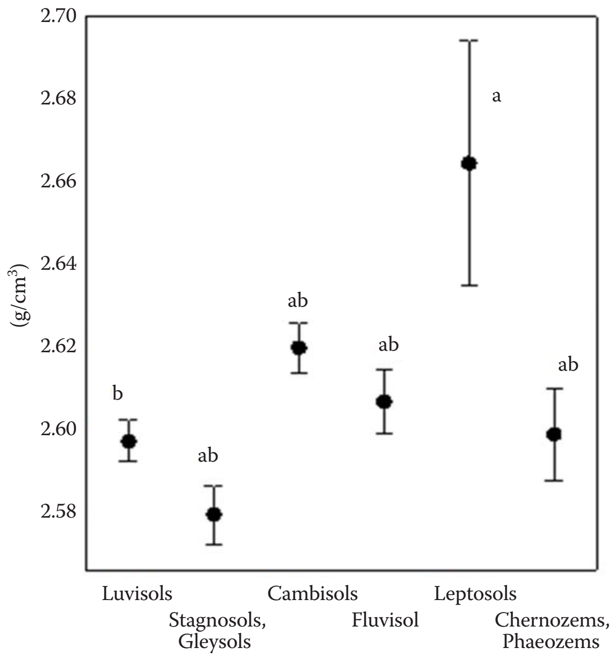

Figure 1. The particle density in the topsoil of the agricultural soils (mean ± standard error); the different indexes mark significant ($P < 0.05$) differences (i.e., Luvisols are significantly different from Leptosols)

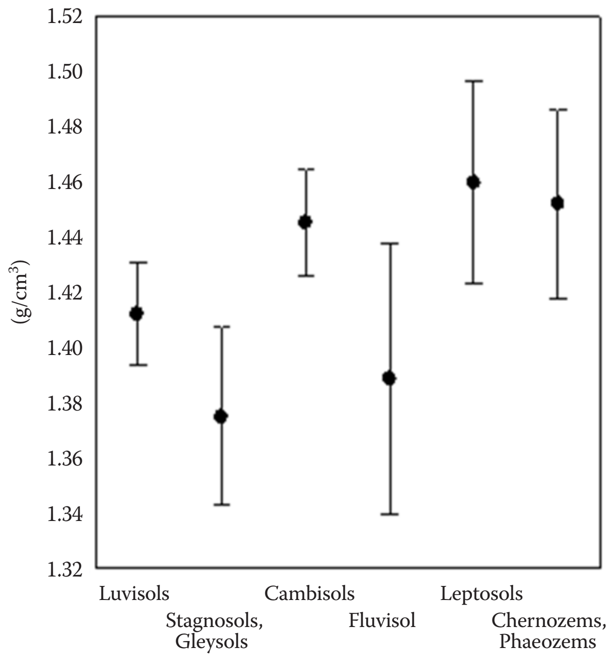

Figure 2. The bulk density in the topsoil of the agricultural soils (mean ± standard error); no significant ($P > 0.05$) differences between the bulk density of the different soil groups were found

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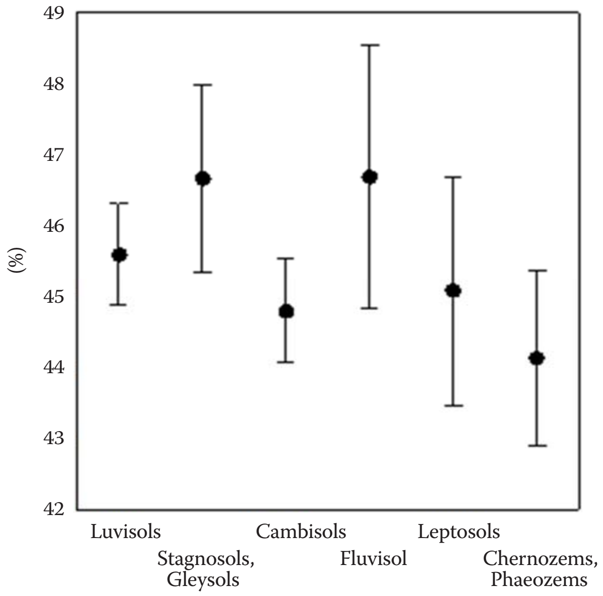

Figure 3. The total porosity in the topsoil of the agricultural soils (mean ± standard error); no significant ($P > 0.05$) differences between the total soil porosity of the different soil groups were found

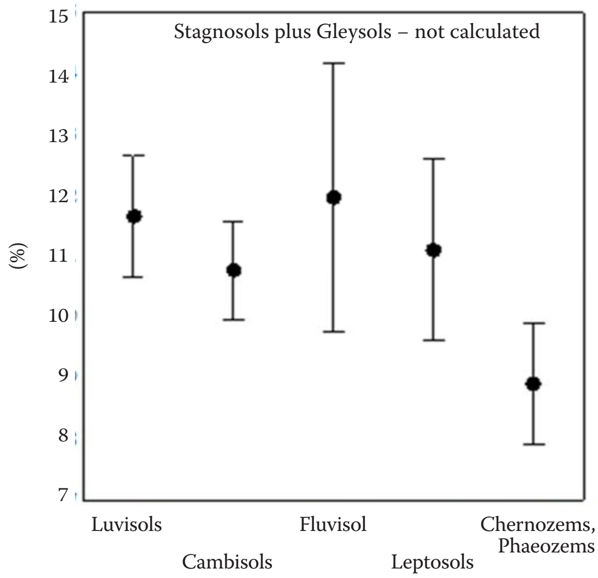

Figure 4. The minimum air capacity in the topsoil of the agricultural soils (mean ± standard error); no significant ($P > 0.05$) differences between the minimum air capacity of the different soil groups were found

the total soil porosity in the topsoil of the different soil groups were found.

The minimum air capacity of the individual samples taken from the topsoil of 47 S-soil pits ranged from 1.2 to 26.9% (Table 1). The highest average minimum air capacity was found in the Fluvisols, Luvisols and Leptosols. The lowest average minimum air capacity was found in the case of the Chernozems plus Phaeozems (Figure 4). An analysis using a one-way ANOVA showed no significant ($P > 0.05$) differences between the minimum air capacity of the different soil groups. Within the period from the GSSAS to 2016–2017, the minimum air capacity decreased in the Leptosols (on average by 21.9%), Cambisols (25.7%), Chernozems plus Phaeozems (>30.0%), Stagnosols plus Gleysols (>30.0%) and increased in the Luvisols (by 28.0%) and Fluvisols (>30.0%).

The maximum capillary water capacity of the individual soil samples taken from 2016 to 2017 ranged from 21.1 to 45.1% (Table 1). The statistically significant ($P < 0.05$) differences between the values of the maximum capillary water capacity in the topsoil of the soil groups are shown in Figure 5. The highest average maximum capillary water capacity was measured in the case of the Stagnosols plus Gleysols and the lowest in the Luvisols and Leptosols (Figure 5). In this comparison study, an increase, on average by 8.3%, 8.3%, 14.2% and 26.9% was found in the Luvisols, Leptosols, Cambisols, Chernozems plus Phaeozems, respectively. The maximum capillary water capacity decreased in the Fluvisols by 0.3% and Stagnosols plus Gleysols (8.5%).

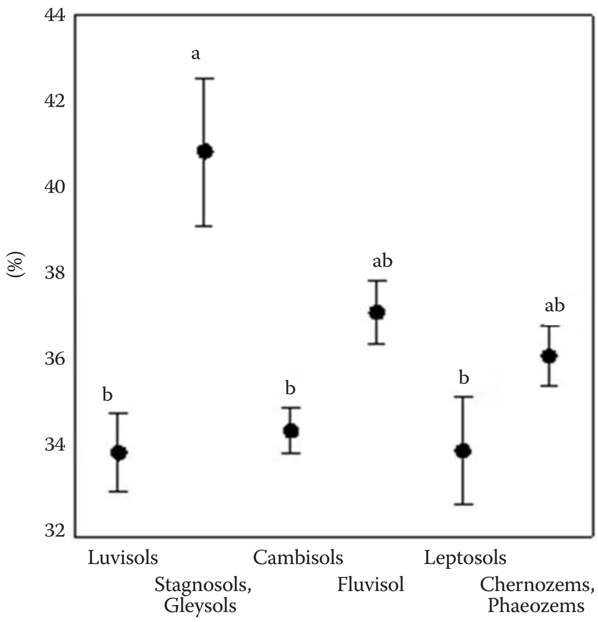

Figure 5. The maximum capillary water capacity in the topsoil of the agricultural soils (mean ± standard error); the different indexes mark significant ($P < 0.05$) differences (i.e., Luvisols, Cambisols or Leptosols are significantly different from Stagnosols plus Gleysols)

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As reported in the work by Sáňka and Materna (2004), the average values of the bulk density found in the topsoil during Basal monitoring of agricultural soils (BMAS) in the Czech Republic range from 1.17 to 1.45 g/cm^3 (Sáňka & Materna 2004). Jorbenadze et al. (2017) listed the values of the bulk density in the topsoil from Georgia in the range of 0.91 g/cm^3 (Dystric Gleysols, Eutric Gleysols and Histosols) to 1.43 g/cm^3 (Stagnic Acrisols and Ferric Acrisols). Sáňka and Materna (2004) listed the average values of the total soil porosity found in the topsoil during the BMAS in the range of 45.25 to 55.25%. The average values of the maximum capillary water capacity found in the topsoil during the BMAS in the range of 30.73–46.48% are listed in the work by Sáňka and Materna (2004).

The bulk density and total soil porosity fluctuate depending on the year, soil depth and soil cultivation, and catch crop (Filho & Tessier 2009; Irmak et al. 2018), the bulk density correlates with the total porosity and is an indicator of the soil compaction (Hemmat et al. 2010). Malhi et al. (2008) found significant effects of tillage, rotation and the previous crops in the rotation on the bulk density at a depth of 0–5 cm in some years. Šimečková et al. (2016) reported a positive effect of the application of a digestate or manure on the bulk density, total soil porosity and minimum air capacity.

Some examples of good agricultural practices with a positive effect on soil physical properties are mentioned below. Liu et al. (2019) found that ten years of organic planting increased the total soil porosity and soil organic matter content and decreased the bulk density. Edmeades (2003) found the long-term effect of manures on the bulk density, total soil porosity, hydraulic conductivity and aggregate stability, which was positive when compared with the use of fertilisers. Aranyos et al. (2016) studied the effect of a sewage sludge compost application on the physical properties of sandy soil. The authors concluded that only high compost doses have a long-term effect on the bulk density due to the mineralisation of the applied organic matter. Meng et al. (2019) found that the long-term application of manure to sodic soil decreased the bulk density. Irmak et al. (2018) compared the historical values of the bulk density measured in 1974 with those measured in 2016 and indicated that incorporating cover crops in seed maize or soybean rotations does not have a long-term effect on the bulk density. Filho and Tessier (2009) studied the effect of tillage on the soil porosity for a period of 31 years. The authors found not significantly lower porosity responsible for the drainage and aeration under conventional tillage compared to the no-tillage. No significant differences were found by Filho and Tessier (2009) in the case of the other pore classes. Bogunovic et al. (2014) concluded that a significant effect of tillage systems on the bulk density and total soil porosity was present at most soil depths.

Soil hydrologic coefficients. The field capacity of the topsoil of 43 S-soil pits ranged from 0.211 to 0.375 m^3/m^3 (Table 2). The highest average values of the field capacity were measured in the Chernozems,

Table 2. The field capacity, permanent wilting point and available water capacity in the topsoil of 43 specific (S) soil pits (minimum–maximum)

USDA textural classification	Field capacity	Permanent wilting point	Available water capacity
		(m^3/m^3)	
Sandy loam (Cambisols, Luvisols, Fluvisols, Leptosols, Stagnosols plus Gleysols)	0.231–0.375	0.068–0.221	0.137–0.210
Loam (Cambisols, Luvisols, Chernozems, Leptosols, Stagnosols plus Gleysols)	0.211–0.363	0.083–0.224	0.108–0.210
Silty loam (Cambisols, Luvisols, Fluvisols, Chernozems, Stagnosols plus Gleysols)	0.236–0.362	0.138–0.258	0.080–0.169
Sandy clay loam (Chernozems)	0.375	0.221	0.154
Silty clay loam (Luvisols, Fluvisols, Chernozems)	0.294–0.303	0.170–0.243	0.060–0.125
Clay loam (Fluvisols, Leptosols)	0.294–0.311	0.203–0.214	0.080–0.108

USDA – U.S. Department of Agriculture; USDA textural classification – classification according to the Soil Science Division Staff (2017)

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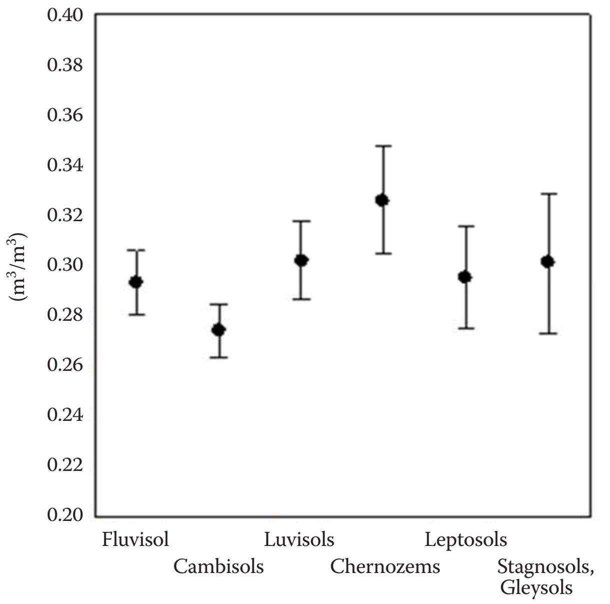

Figure 6. The field capacity in the topsoil of the agricultural soils (mean ± standard error); no significant ($P > 0.05$) differences between the field capacity of the different soil groups were found

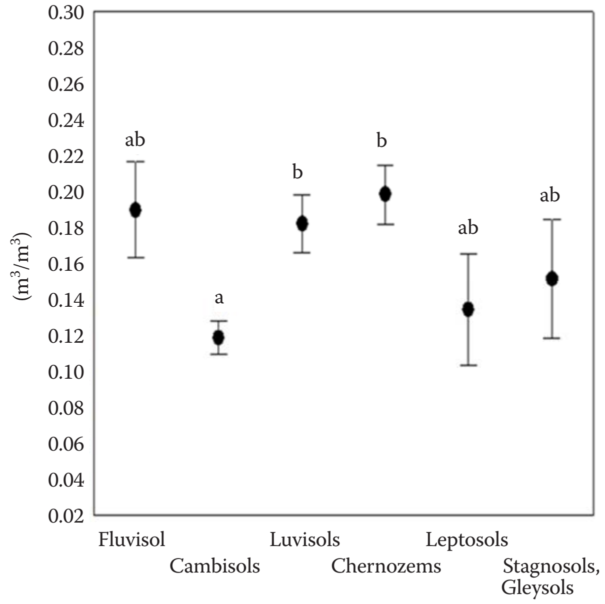

Figure 7. The permanent wilting point in the topsoil of the agricultural soils (mean ± standard error); the different indexes mark significant ($P < 0.05$) differences (i.e., Cambisols are significantly different from Luvisols and Chernozems)

Stagnosols plus Gleysols and Luvisols (Figure 6). A statistical analysis using a one-way ANOVA showed no significant ($P > 0.05$) differences between the values of the field capacity in the topsoil of the soil groups. The permanent wilting point of the soil samples from the individual S-soil pits ranged from 0.068 to 0.258 m^3/m^3 with the highest average values in the Chernozems, Fluvisols and Luvisols (Figure 7). The available water capacity range was 0.06–0.21 m^3/m^3 (Table 2). The highest average available water capacity was calculated for the topsoil of the Leptosols, Cambisols and Stagnosols plus Gleysols and the lowest was for the topsoil of the Fluvisols (Figure 8). A statistical analysis showed significant ($P < 0.05$) differences between the values of the permanent wilting point and the available water capacity in the topsoil of the studied soil groups that are shown in Figures 7 and 8. The field capacity, permanent wilting point and available water capacity in the topsoil of the most frequent textural classes (sandy loam, loam and silty loam) were compared. No significant ($P > 0.05$) differences were found between the field capacity in the topsoils of the different textural classes. A statistical analysis showed significant ($P < 0.05$) differences between the values of the permanent wilting point as well as the available water capacity in the topsoil of the sandy loam texture and the topsoil of the silty loam texture (Table 3).

The values of the field capacity and permanent wilting point obtained in this work are approximately in the range reported by Šarapatka (2014) and Allen et al. (1998) for mineral soils of different textures.

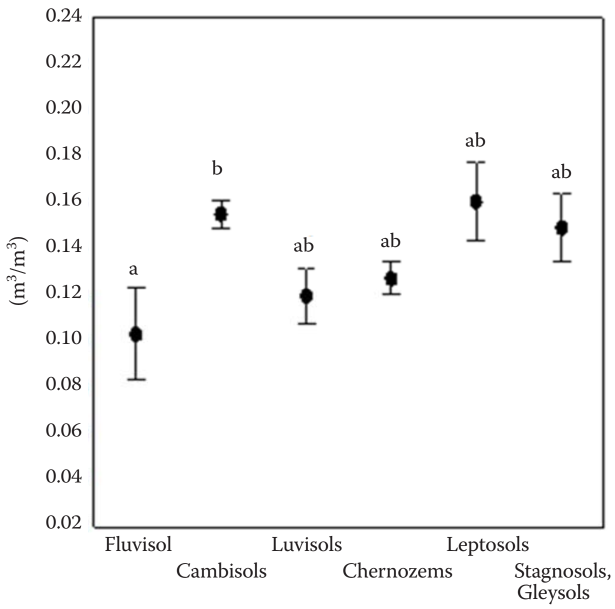

Figure 8. The available water capacity in the topsoil of the agricultural soils (mean ± standard error); the different indexes mark significant ($P < 0.05$) differences (i.e., Fluvisols are significantly different from Cambisols)

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Table 3. The field capacity, permanent wilting point and available water capacity in the topsoil of the different textural classes (mean ± standard error)

USDA textural classification	Field capacity	Permanent wilting point	Available water capacity
		(m^3/m^3)	
Sandy loam	0.28 ± 0.01[a]	0.12 ± 0.01[a]	0.16 ± 0.005[a]
Loam	0.28 ± 0.02[a]	0.14 ± 0.02[ab]	0.14 ± 0.01[ab]
Silty loam	0.31 ± 0.12[a]	0.19 ± 0.01[b]	0.12 ± 0.01[b]

USDA – U.S. Department of Agriculture; USDA textural classification – classification according to the Soil Science Division Staff (2017); the different indexes mark significant ($P < 0.05$) differences between the values in the same column

Šarapatka (2014) reported ranges for the field capacity of 10–40 (50)% and for the permanent wilting point of 2–30% and Allen et al. (1998) reported 7–42% (field capacity) and 2–29% (permanent wilting point). Grewal et al. (1990) listed the mean values in the range of 20–57.4% (field capacity) and 9.6–41.8% (permanent wilting point) for sandy loam, silt loam, clay loam and clay. Jorbenadze et al. (2017) listed the values of the permanent wilting point in different soils from Georgia in the range of 7.1% (Gleyic Fluvisols, Eutric Fluvisols and Dystric Fluvisols) to 24.8% (Calcic Kastanozems and Vertic Kastanozems). Da Costa et al. (2013) also showed the dependence of the field capacity and permanent wilting point on the soil texture. The authors reported a range of 0.16–0.55 m^3/m^3 (field capacity) and 0.07–0.39 m^3/m^3 (permanent wilting point) in the surface horizon with the highest values in clay and silty clay loam and the lowest in sand. Da Costa et al. (2013) found a higher field capacity and permanent wilting point of the surface horizon, for example, in Cambisols, intermediate in Leptosols and Chernozems, and lower in Arenosols. Organic matter often increases the field capacity more than the permanent wilting point and it has a positive effect on the available water capacity (Huntington 2006). An available water capacity range of 0.09 to 0.17 m^3/m^3 in soils of different textures is listed in the work by da Costa et al. (2013). Some examples of good agricultural practice with a positive effect on the soil hydrologic coefficients are mentioned below. Šimečková et al. (2016) reported that the application of a mineral fertiliser had a positive effect and the application of a manure or digestate had a negative effect on the field capacity at a depth of 5 cm. The positive effect at the depth of 15 cm was found due to the application of a digestate (Šimečková et al. 2016). Irmak et al. (2018) compared the historical values for the field capacity and permanent wilting point when no cover crops were planted in the fields with those measured after the long-term (> 40 years) cultivation of cover crops. In the topsoil, the field capacity increased on average by 5% and the permanent wilting point increased on average by 20% (Irmak et al. 2018).

CONCLUSION

Overall, many of the studied physical topsoil properties do not differ significantly among the individual soil groups. These non-significant ($P > 0.05$) differences were found in the case of the bulk density and the total soil porosity, the minimum air capacity and the field capacity, probably because this topsoil is influenced by long-term agricultural management practices. The only exceptions are the particle density, the maximum capillary water capacity and some hydrologic coefficients, such as the permanent wilting point and the available water capacity calculated from the field capacity and the permanent wilting point. After more than 40 years, the bulk density and the maximum capillary water capacity increased and the total porosity and the minimum air capacity decreased in the topsoil of the major part of the studied soil groups. A decrease in the bulk density and an increase in the total porosity in the topsoil were evident in the case of Luvisols.

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