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Interaction of silty loam soil on the change of soil retention capacity and soil compaction following subsoiling

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Abstract: The subsoiling of arable soils as part of a strategy against excessive compaction and the resulting plow pan can be successfully used as a pro-retention treatment. The study of changes in the physical and water properties of soil as a result of subsoiling was carried out on three sites: Wojnowice, Strzybnik, and Owsiszcze, located in the Racibórz district, Śląskie Voivodeship (Poland), in a silty-loam soil. A total of five soil profiles (0–150 cm) were analyzed before and after subsoiling. The experiment used a seven-tine Maschio subsoiler at a depth of 50–60 cm between 2012–2014. The physical (e.g., soil bulk density, soil organic matter) and water (e.g., maximum water capacity, field water capacity, permanent wilting point, total plant available water) properties of the soil were determined before and after subsoiling, taking into account the division into layers: 0–25 cm, 25–50 cm, and 50–150 cm. Statistical analyses were used to check changes in soil physical and water parameters. The results show that the subsoiling treatment caused a statistically significant decrease in soil compaction (bulk density) at all three layers and increased moisture in the range of total plant available water in the subsoil layer (25–50 cm). Subsoiling in silty-loam soil will enable the soil's retention potential to be used, especially in dry years.

Keywords: soil compaction, subsoiling, soil moisture, climate change, sustainable agriculture

INTRODUCTION

Sustainable water management in agriculture and water-dependent ecosystems is one of the greatest challenges of the 21st century, particularly concerning current climate change (Allan et al. 2013, Misra 2014, Cosgrove & Loucks 2015, Hameed et al. 2019). To solve problems with water and especially its shortage, which affects millions of people around the world, it is necessary, among other things, to identify the key agricultural mechanisms associated with soil cultivation processes (Iglesias & Garrote 2015).

Soil is potentially one of the largest "water reservoirs", and its rational use could ensure environmental stability and sustainability (Reichardt & Timm 2020). Unfortunately, the water potential of most soils in the world is not exploited.

Knowledge of the fundamental soil moisture characteristics (such as maximum water capacity, field water capacity, or permanent wilting point and available water content) supports efficient and rational water management in agriculture. The main root mass of cultivated plants reaches a depth of 50 cm, with some growing roots deeper. This means that it is crucial to provide adequate moisture in this part of the profile, which could be used by the plant root system using the capillary rise phenomenon and thus nourish the plant during periods of rainfall deficit (Ghosh & Daigh 2020).

When speaking about the retention capacity of the soil, it should be borne in mind that not only does its textural composition play a significant role here, but it also plays a role in its maintenance – the method of cultivation and fertilization. It may transpire that after some time, ordinary shallow and traditional plowing will not bring the desired results related to soil retention. The world's soils are increasingly exploited, stressed, and degraded (Ning et al. 2022). Excessive soil compaction leads to poor water conductivity and retention. This problem particularly affects heavy (clayey) soils that are intensively exploited and where heavy tillage machines are used, which intensify the compaction phenomenon resulting in the formation of the "plow pan".

Soil, which is still the basic medium and factor of production, is becoming increasingly degraded and contaminated with heavy metals (Aleksander-Kwaterczak & Rajca 2015). Using soil through appropriate agricultural techniques – loosening and improving its structure – brings the desired benefits. In addition to the solid phase, the appropriate relationship between the gas and water phases in the soil profile is extremely important for plant growth and development.

Monitoring changes in the physical properties of soil, resulting from how it is cultivated and affecting water retention, would often be useful for a comprehensive solution to water management problems in soil for agricultural purposes. Water in soil comes mainly from atmospheric precipitation (Zhang et al. 2010, Xu et al. 2012, Zhao et al. 2014). Climate change observed in recent years, in particular the increase in air temperatures and the frequency of heavy rainfall, limits soil water retention, resulting in droughts and inhibition of plant life processes (Senapati et al. 2019). Therefore, climate is an important factor influencing rational water management in agriculture (Karmakar et al. 2016).

Precipitation of 1 mm provides 10 m^3 of water per hectare (Mioduszewski 2014). Therefore, precipitation is a significant water source in soil. Water can be retained through costly and time-consuming technical measures (river dams, irrigation systems, reservoirs, etc.) or much cheaper and faster to implement non-technical (agricultural) activities, which are often sufficient to achieve satisfactory results (Liu et al. 2013, Mioduszewski 2014, Iglesias & Garrote 2015, Siegmund-Schultze et al. 2018).

The most important for agricultural crop production (for agricultural practice) are water resources that can be determined using the soil water retention curve (SWRC) (van Genuchten 1980) with pF between field capacity (FC) and permanent wilting point (PWP), i.e., the range taken as total plant available water (PAW) (Martínez et al. 2012, Silva et al. 2014, Dobarco et al. 2019). In this range, readily/easily available water (RAW) is distinguished, corresponding to the difference between FC and temporary wilting point (TWP). In contrast, with pF between TWP and PWP, water is hardly available (HAW) (Bourrié 2018).

Dodd and Lauenroth (1997) reported that soil texture and tillage have a major impact on water distribution in the soil profile. Sandy soils are well permeable but have low water capacity, while silty and loamy soils have high compactness and low permeability but have much higher water capacity. Since these soils are naturally fertile and productive, farmers use practices to aerate them and improve water infiltration. One such practice is subsoiling with a subsoiler, which reduces soil compaction and improves air-water relations in the soil profile. Subsoiling loosens the soil profile up to a depth of 1.00 m and is mainly recommended in fields with tramlines and headlands or on high-density arable soils as it helps to eliminate the "plow pan" and avoid the depletion of the soil's organic matter.

This study assessed the changes in physical and water properties in silty-loam soil. It was hypothesized that subsoiling reduces compaction and improves the water storage capacity of the soil profile.

MATERIALS AND METHODS

Site description

The study was conducted in southern Poland (Fig. 1) in three locations: Wojnowice, Strzybnik, and Owsiszcze, situated in Racibórz District in the southern part of the Śląskie Voivodship.

The physical-geographic division of the Racibórz district, including the location of research sites, land use and soil characteristics is presented in Figure 2.

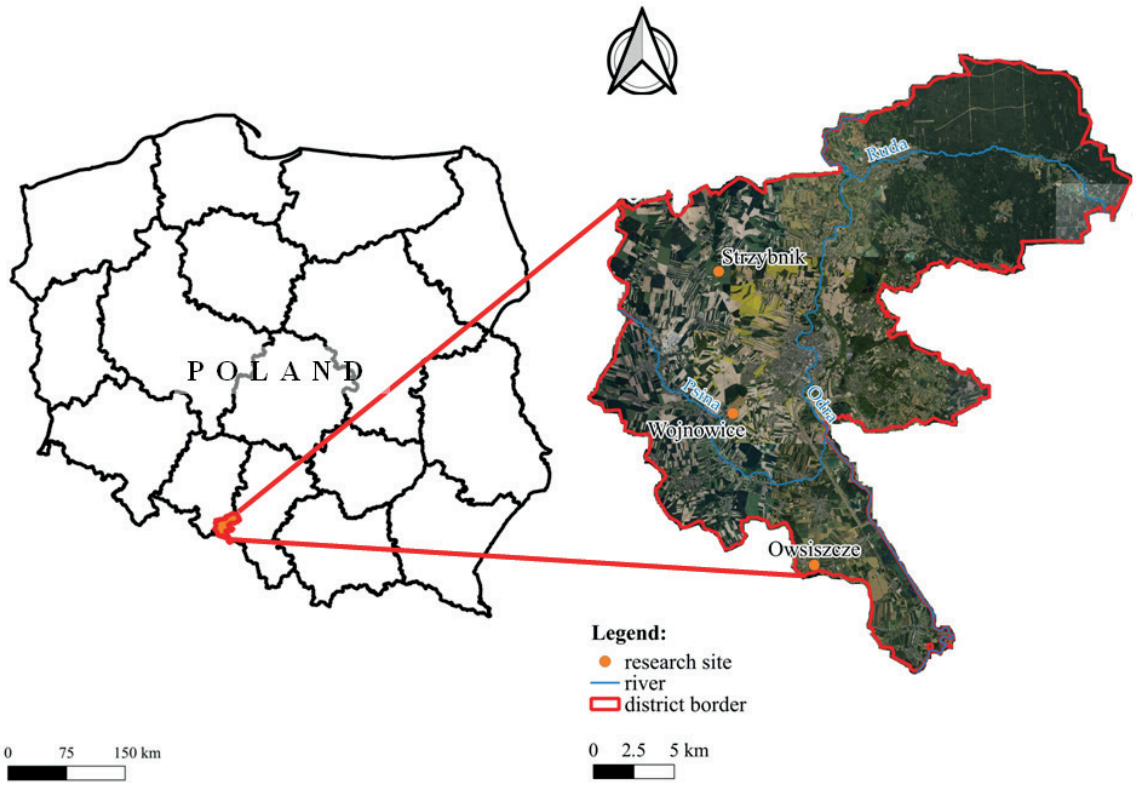
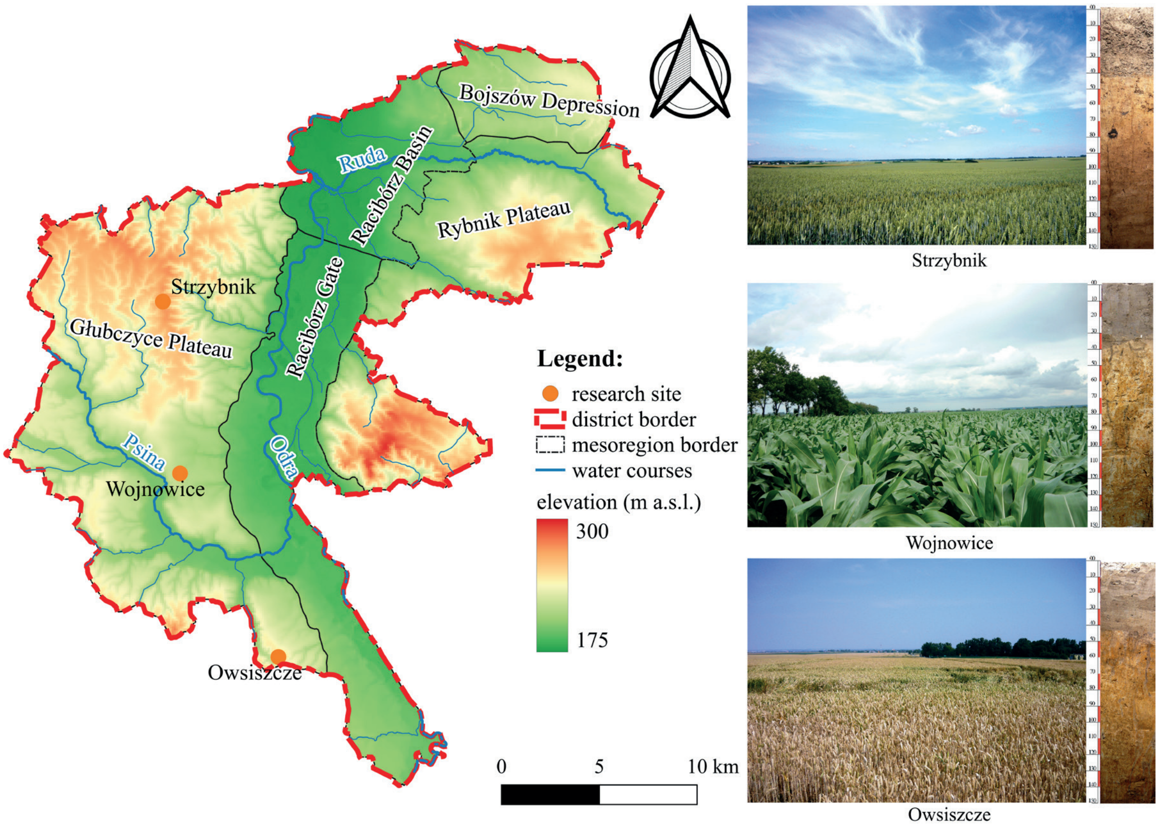


Fig. 1. Administrative location of study area



Strzybnik

Wojnowice

Owsiszcze

Fig. 2. The physical-geographic division of the Racibórz district

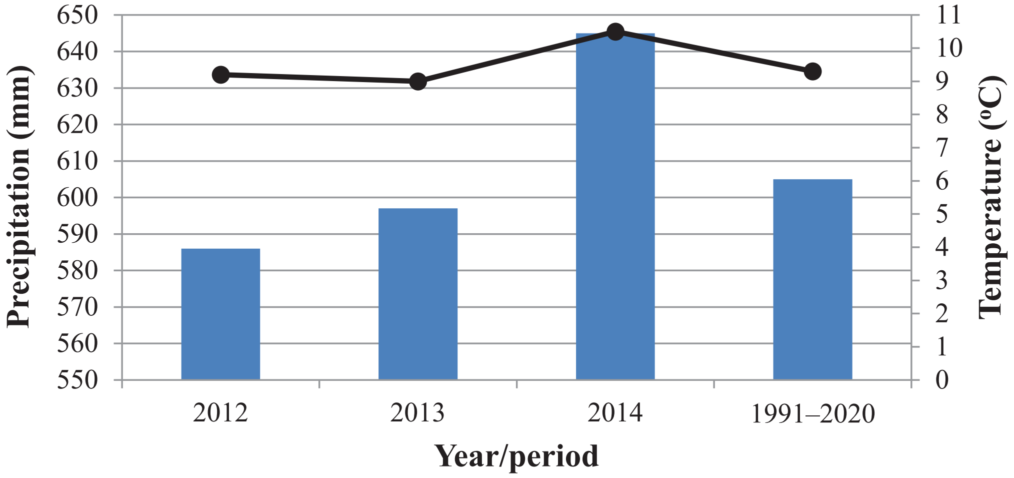


Fig. 3. *Average air temperatures [°C] and total precipitation [mm] in the study years in comparison to the multiannual period 1991–2020 (background)*

The studied objects, in terms of physiogeography, are located in the province of the Central European Lowland, the subprovince of the Central Poland Lowlands, in the macroregion of the Silesia Lowland in mesoregions: the Głubczyce Plateau (Richling et al. 2021). It is a rolling loess plain with small hills, dissected by deeply incised valleys. The elevation is between 175 and 300 m above sea level (a.s.l.) (Wojnowice – 215.00 m a.s.l., Strzybnik – 260.00 m a.s.l., Owsiszcze – 235.00 m a.s.l.). The hydrographic network of the Racibórz district consists of the Odra River and its smaller tributaries – the Psina and Ruda rivers (Fig. 2). This region is currently one of Poland's most important cereal and vegetable crops. The main crops grown here are wheat and corn. Plough tillage is carried out here and the soil cover consists of lessive and brown soils (Fig. 2).

The main role in the water requirements of plants is played primarily by climatic factors (precipitation, temperature, etc.) and the physical properties of the soil. The variability of climatic conditions over time creates the risk of disturbing the balance of soil water management. Understanding the climatic and soil conditions allows the selection of the appropriate agricultural technology to facilitate water storage or drainage. According to the Köppen–Geiger climate classification (Kottek et al. 2006), the regional climate is temperate (Cfb) with an average annual temperature of 9.3°C and an average annual precipitation of 605 mm (Fig. 3).

Experiment design

A seven-tine Maschio subsoiler was used in the field experiment (Fig. 4). Tines were arranged into two rows with individual spacing of 50 cm and at a working depth of 50–60 cm.

A total of five soil profiles were made in soils with traditional plough cultivation (T) – one in Wojnowice, one in Strzybnik and three in Owsiszcze and five after subsoiling (S) – one in Wojnowice, one in Strzybnik and three in Owsiszcze. Research was performed for each soil profile in three separate layers (0–25 cm, 25–50 cm, 50–150 cm). In the field, soil samples of intact (using Kopecký steel cylinders) and disturbed structure were collected and processed further in the laboratory.

At the Wojnowice and Strzybnik sites, soil subsoiling was performed in October 2011. Subsoiling covered the outer sections of the agricultural parcels most susceptible to compaction (so-called headlands, which are strips of land on the edges of a field, used to turn agricultural machinery during field work). On the remaining parts of the parcels, traditional farming techniques were used. The research and collection of soil samples for analysis were carried out on both parts of the agricultural parcels in June 2012.

Fig. 4. *Maschio subsoiler while working in the field*

At the Owsiszcze site, subsoiling was performed in August 2014 on the headlands of the agricultural parcel. The tests and soil sampling before subsoiling were carried out in July 2014 and after subsoiling in October 2014.

Laboratory analysis

The textural composition of all soil samples was determined using the Bouyoucos–Casagrande areometric method modified by Prószyński (Mocek & Drzymała 2010). The modification consisted of measuring soil suspension using the Prószyński areometer, which gives the percentage of sedimentation fraction between two readings taken at different points in time. Suspension density is read at dates specified in tables prepared by Prószyński. The content of sand fraction (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) was determined according to the soil taxonomy system which was announced by the United States Department of Agriculture (USDA) (Soil Survey Staff 1999).

Soil bulk density (BD) was determined by the drying-weighing method using Kopecký steel cylinders (Mocek & Drzymała 2010). The assessment of soil compaction was made based on the BD value, which depends on the texture, soil organic matter content and agrotechnical treatments (Paluszek 2011). The optimal range of BD in arable soils should be within 0.9–1.2 $\mathrm{Mg \cdot m^{-3}}$ for maximal field crop production, values greater than 1.25–1.30 $\mathrm{Mg \cdot m^{-3}}$ potentially causing yield loss due to inadequate soil aeration, and values below 0.9 $\mathrm{Mg \cdot m^{-3}}$ potentially causing yield loss due to inadequate plant anchoring, reduced PAW capacity, and reduced unsaturated flow of water and dissolved nutrients to plant roots (Reynolds et al. 2009). According to USDA (Soil Survay Staff 1999) ideal bulk density values affecting root growth for silt loams is <1.30 $\mathrm{Mg \cdot m^{-3}}$, marginal 1.60 $\mathrm{Mg \cdot m^{-3}}$ and restrictive >1.75 $\mathrm{Mg \cdot m^{-3}}$.

Soil organic matter (SOM) was determined using the Tiurin method (Mocek & Drzymała 2010), which first determined the organic carbon content (C_{org}) in the sample and then multiplied the obtained value by 1.724 (van Bemmelen factor).

The water retention in the soil was determined using ceramic plates in 5- and 15-bar Eijkelkamp's pressure plate extractors produced by the American Soil Moisture Equipment Corporation (photo). In engineering practice, soil suction power is usually given in pF units (Schofield 1935):

$$\mathrm{pF} = \log h \ [\mathrm{cm\ H_2O}],$$

where h is the soil matric potential [cm].

The determination of the points of the SWRC in the low water potential range, i.e., pF 0.0–3.0, was performed using ceramic plates in low-pressure chambers/extractors (by Eijkelkamp, manufactured by American Soil Moisture Equipment Corporation) displacing water from intact soil samples placed in 100 cm^3 metal cylinders, in 2–3 repetitions for each of the soil matric potential.

The determination of the points of the SWRC in the high-water-potential range, i.e., pF 3.4–4.2, was performed using ceramic plates in high-pressure chambers/extractors (by Eijkelkamp, manufactured by American Soil Moisture Equipment Corporation) displacing water from previously prepared intact soil samples (semi-liquid slurry/soil mixture) placed in rings 1 cm high, in 2–3 repetitions for each of the soil matric potential.

The samples were kept in pressure chambers for 24 hours, weighed on a precision laboratory scale with a measurement accuracy of 0.001 g, and dried in a dryer at 105°C for 48 hours. After drying, the samples were weighed again, and the water content in the soil by volume ($m^3 \cdot m^{-3}$) was calculated.

The FC for mineral soils with low groundwater levels was assumed at pF 2.5, the TWP at pF 3.7, and the PWP at pF 4.2 (Mocek & Drzymała 2010). Gravitational water (GW) is the difference between full water capacity at pF 0.0 and field capacity at pF 2.5. Total PAW means water content between pF 2.5 and pF 4.2. Within these limits, RAW between pF 2.5–3.7 and HAW between pF 3.7–4.2 were distinguished.

Analyses were performed for each separated layer, with a minimum of three replicates for the 0–25 cm and 25–50 cm layers and more than three replicates for the 50–150 cm layers. For large differences (>5%), the result was rejected and not included in further calculations. The final sample sizes (*n*) are given in the results tables (Tables 1–3).

Data analysis and visualization

To check the effect of subsoiling on the physical and water properties of the soil, the TIBCO Software Inc. Statistica package (version 13.3 PL) was used to determine basic descriptive statistics of variables such as minimum (Min.), maximum (Max.), average, median, standard deviation (SD), and coefficient of variation (CV). The interpretation of the CV coefficient was made based on the following scale: less CV < 20%, moderate 20% < CV < 30%, high CV > 30%, and very high CV > 40% (Brown 1998). Then, the significance of differences before and after subsoiling was checked. In the case of fulfilling the assumption of normal distribution and homogeneity of variance, the *t*-test for dependent samples or the Wilcoxon test in other cases. Analyses were performed at a significance level of 0.05. Kruskal–Wallis ANOVA analysis was used to check the changes in physical and water properties before and after subsoiling between layers in the vertical soil profile (Stanisz 2006). The location of the research sites was visualized in QGIS 3.4. The tables and selected figures were prepared in MS Excel 2019.

RESULTS AND DISCUSSION

Selected physical and water properties for soils with traditional tillage (T) and soils after subsoiling (S), together with basic descriptive statistics and test probability, are presented in Tables 1–3. Changes in physical and water properties in soil profiles before and after subsoiling are shown in Figure 5. The analysis of the results of granulometric composition determinations, according to the USDA (Soil Survey Staff 1999) soil texture classification, allowed the classification of the tested three separate soil layers as silty loam soils.

The BD value after subsoiling in each layer was lower than in the soil before subsoiling (Tables 1–3, Fig. 5A). On average, the difference was 8.9% for the first layer (0–25 cm), 3.1% for the second layer (25–50 cm) and 2.4% for the third layer (50–150 cm) (Fig. 1A), and for the first and second layers these differences were statistically significant ($P < 0.05$) (Tables 1–3). For both types of cultivation, the bulk density of individual layers showed low variability (CV).

The average BD increased with depth both in the soil before and after subsoiling (Fig. 5A). The average BD values were the lowest in the 0–25 cm layers (loosened soil) and the highest in the 50–150 cm layers (compacted soil). Considering the distribution of BD values in the vertical soil profile (Table 4), it can be stated that in the case of the non-subsoiled soil, the BD value in the second layer increased on average by 3.1% compared to the first layer. Still, this increase was statistically insignificant ($P > 0.05$). In the third layer, a further insignificant ($P > 0.05$) increase in soil compaction was observed by about 3.0% compared to the second layer and a significant increase by 6.0% ($P < 0.05$) compared to the first layer. In the subsoiled soil, the mean differences in BD values between the first, second, and third layers were statistically significant ($P < 0.05$) by 8.9% and 12.2%, respectively. In contrast, between the second and third layers the average BD values were statistically insignificant ($P > 0.05$), and the difference was 3.7% (Table 4).

Soil compaction caused by soil texture and the movement of heavy agricultural machinery increases BD (Ghosh & Daigh 2020, Shaheb et al. 2021). Studies conducted by Panagos et al. (2024) in the European Union showed that at a depth of 10–20 cm the BD is 5–10% higher compared to the density at a depth of 0–10 cm for all land use types. Therefore, it seems reasonable to use subsoiling, which loosens the soil, especially the subsoil layers characterized by higher density. As indicated by this study and others (Evans et al. 1996, Drewry et al. 2000, Leskiw et al. 2012, Wang et al. 2019, Fan et al. 2025), subsoiling significantly affects not only the surface layer of the soil but also – which is important from the point of view of water conductivity – the subsurface layers of the soil. The conducted analyses and studies by Wang L.Q. et al. (2024) show that subsoiling reduces the BD of the soil and increases its porosity.

Soil loosening increases both water infiltration and drainage (Borek et al. 2021), which may affect the leaching of nitrogen compounds from the soil profile (Pikul & Aase 2003). This cause-and-effect relationship indicates the need to research this area and monitor the magnitude of changes in physical and water parameters in the soil due to subsoiling treatment.

Table 1
The characteristics of the soil properties before (T) and after (S) subsoiling in 0–25 cm layer

Soil properties	Unit	Crop type	*n*	Min.	Max.	Average	Median	SD	CV	*P**
BD	$Mg{\cdot}m^{-3}$	T	13	1.48	1.70	1.58	1.57	0.07	4	0.0029^{W}
		S	13	1.32	1.63	1.44	1.41	0.10	7	
SOM	%	T	13	1.00	1.40	1.15	1.10	0.13	11	0.1797^{W}
		S	13	1.00	1.40	1.17	1.15	0.13	11	
pF 0.0	$m^{3}{\cdot}m^{-3}$	T	13	0.3730	0.4200	0.3957	0.3913	0.0168	4	0.0015^{W}
		S	13	0.3812	0.4672	0.4373	0.4489	0.0258	6	
pF 2.5		T	13	0.1973	0.3719	0.3085	0.3253	0.0534	17	0.2787^{W}
		S	13	0.2887	0.3678	0,3262	0,3228	0.0220	7	
pF 3.7		T	13	0.1355	0.2206	0.1586	0.1523	0.0216	14	1.0000^{W}
		S	13	0.1383	0.2206	0.1613	0.1533	0.0213	13	
pF 4.2		T	13	0.0955	0.1416	0.1202	0.1245	0.0150	13	0.2933^{t}
		S	13	0.0955	0.1366	0.1224	0.1253	0.0124	10	
GW		T	13	0.0137	0.2187	0.0872	0.0692	0.0594	68	0.1961^{W}
		S	13	0.0584	0.1439	0.1110	0.1148	0.0281	25	
PAW		T	13	0.0694	0.2649	0.1883	0.1944	0.0581	31	0.2126^{t}
		S	13	0.1598	0.2602	0.2038	0.2026	0.0300	15	
RAW		T	13	0.0618	0.2336	0.1499	0.1692	0.0524	35	0.2016^{t}
		S	13	0.0955	0.2178	0.1650	0.1671	0.0341	21	
HAW		T	13	0.0076	0.0867	0.0384	0.0377	0.0226	59	0.9089^{t}
		S	13	0.0138	0.0867	0.0388	0.0346	0.0197	51	

* Probability (*P*) of paired *t*-test (*t*) or Wilcoxon test (*W*).
Red color indicates significant differences at $P < 0.05$.

Table 2

The characteristics of the soil properties before (T) and after (S) subsoiling in 25–50 cm layer

Soil properties	**Unit**	**Crop type**	***n***	**Min.**	**Max.**	**Average**	**Median**	**SD**	**CV**	***P****
BD	Mg·m^{-3}	T	13	1.57	1.70	1.63	1.62	0.04	2	0.0067^t
		S	13	1.51	1.65	1.58	1.57	0.04	3	
SOM	%	T	13	0.20	1.30	0.78	0.80	0.35	46	0.2851^W
		S	13	0.20	1.30	0.80	0.80	0.33	41	
pF 0.0	m^3·m^{-3}	T	13	0.3685	0.4010	0.3827	0.3834	0.0106	3	0.0007^t
		S	13	0.3870	0.4210	0.4005	0.3990	0.0113	3	
pF 2.5		T	13	0.2816	0.3366	0.3188	0.3204	0.0135	4	0.0014^W
		S	13	0.3137	0.3670	0.3437	0.3463	0.0153	4	
pF 3.7		T	13	0.1269	0.1910	0.1537	0.1523	0.0211	14	0.6257^t
		S	13	0.1269	0.1900	0.1544	0.1583	0.0200	13	
pF 4.2		T	13	0.0841	0.1620	0.1152	0.1128	0.0209	18	0.0679^W
		S	13	0.0902	0.1798	0.1212	0.1131	0.0248	20	
GW		T	13	0.0458	0.1174	0.0639	0.0586	0.0182	29	0.2213^W
		S	13	0.0312	0.0993	0.0568	0.0501	0.0238	42	
PAW		T	13	0.1509	0.2434	0.2036	0.2067	0.0226	11	0.0046^W
		S	13	0.1339	0.2505	0.2226	0.2352	0.0338	15	
RAW		T	13	0.1219	0.2013	0.1651	0.1682	0.0250	15	0.0001^t
		S	13	0.1237	0.2297	0.1894	0.1874	0.0291	15	
HAW		T	13	0.0158	0.0672	0.0385	0.0385	0.0178	46	0.1443^t
		S	13	0.0102	0.0682	0.0332	0.0275	0.0186	56	

* Probability (*P*) of paired *t*-test (*t*) or Wilcoxon test (*W*).

Red color indicates significant differences at $P < 0.05$.

Table 3

The characteristics of the soil properties before (T) and after (S) subsoiling in 50–150 cm layer

Soil properties	**Unit**	**Crop type**	***n***	**Min.**	**Max.**	**Average**	**Median**	**SD**	**CV**	***P****
BD	Mg·m^{-3}	T	26	1.57	1.93	1.68	1.68	0.10	6	0.0061^W
		S	26	1.47	1.87	1.64	1.62	0.11	7	
SOM	%	T	26	0.20	0.60	0.33	0.30	0.14	44	0.3454^W
		S	26	0.10	0.60	0.32	0.30	0.16	50	
pF 0.0	m^3·m^{-3}	T	26	0.2794	0.4010	0.3669	0.3645	0.0301	8	0.0152^W
		S	26	0.3100	0.4150	0.3753	0.3863	0.0307	8	
pF 2.5		T	26	0.1905	0.3779	0.3339	0.3417	0.0460	14	0.2478^W
		S	26	0.2550	0.3786	0.3402	0.3434	0.0331	10	
pF 3.7		T	26	0.1375	0.2697	0.1981	0.1977	0.0268	14	0.8738^t
		S	26	0.1228	0.2697	0.1972	0.1984	0.0320	16	
pF 4.2		T	26	0.1080	0.1943	0.1559	0.1587	0.0230	15	0.1399^t
		S	26	0.0871	0.1943	0.1501	0.1513	0.0284	19	
GW		T	26	0.0115	0.1010	0.0330	0.0238	0.0228	69	0.9090^W
		S	26	0.0090	0.0796	0.0351	0.0314	0.0211	60	
PAW		T	26	0.0825	0.2279	0.1780	0.1896	0.0322	18	0.0734^W
		S	26	0.1363	0.2248	0.1901	0.1936	0.0226	12	
RAW		T	26	0.0462	0.1737	0.1358	0.1451	0.0300	22	0.1587^W
		S	26	0.0973	0.1860	0.1430	0.1413	0.0249	17	
HAW		T	26	0.0133	0.0876	0.0422	0.0413	0.0184	44	0.2626^W
		S	26	0.0133	0.1110	0.0471	0.0439	0.0221	47	

* Probability (*P*) of paired *t*-test (*t*) or Wilcoxon test (*W*).

Red color indicates significant differences at $P < 0.05$.

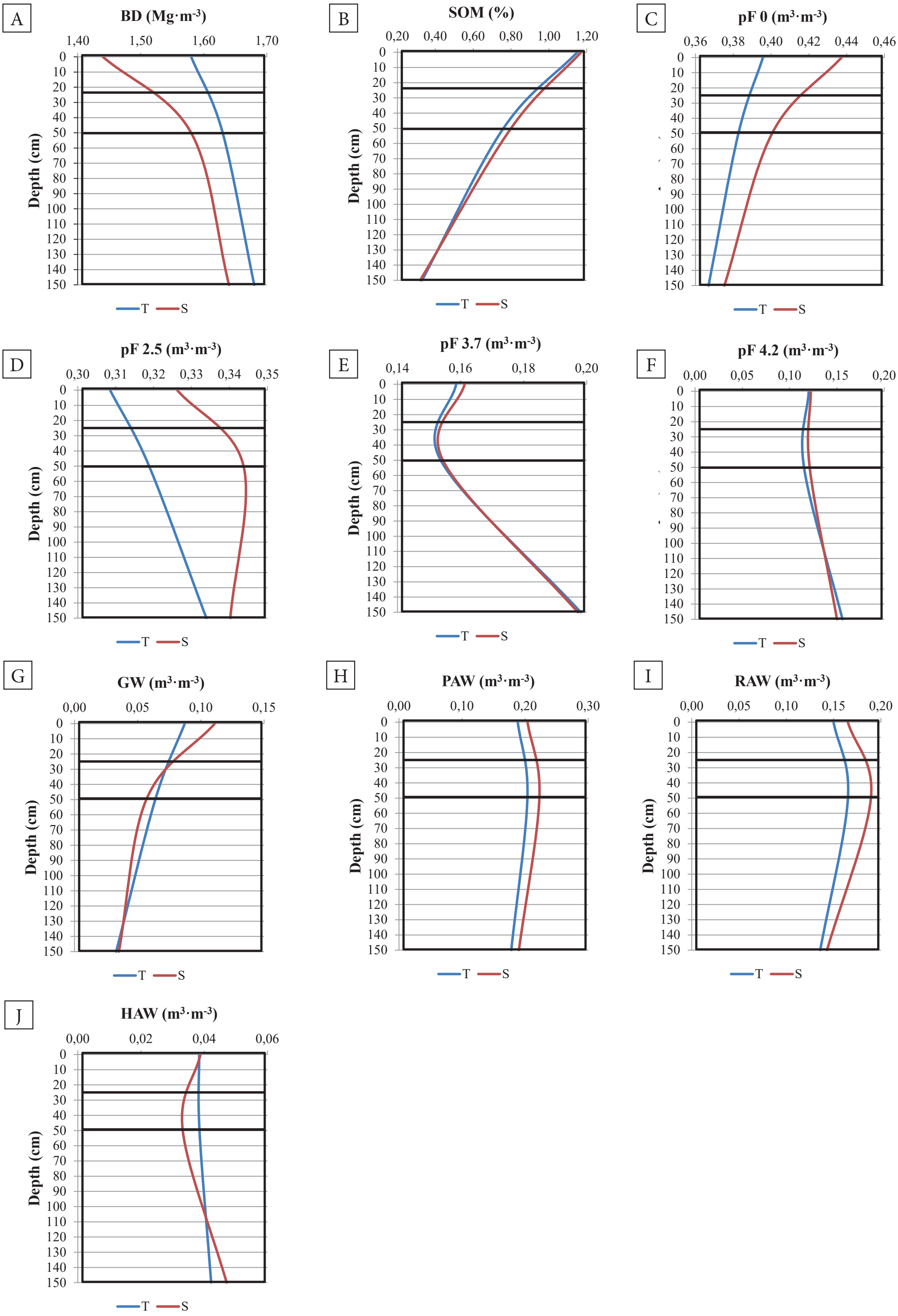


Fig. 5. Changes in physical and water parameters in soil profiles before and after subsoiling

Table 4
Results of the Kruskal–Wallis ANOVA test for three soil layers before and after subsoiling

Soil property	Layer thickness [cm]	Layer thickness [cm]					
		Before subsoiling			After subsoiling		
		0–25	25–50	50–150	0–25	25–50	50–150
BD	0–25	–	0.1845	0.0044*	–	0.0330	0.0000
	25–50	0.1845	–	0.9234	0.0330	–	0.4771
	50–150	0.0044	0.9234	–	0.0000	0.4771	–
SOM	0–25	–	0.1081	0.0000	–	0.1189	0.0000
	25–50	0.1081	–	0.0048	0.1189	–	0.0031
	50–150	0.0000	0.0048	–	0.0000	0.0031	–
pF 0.0	0–25	–	0.2522	0.0022	–	0.0660	0.0000
	25–50	0.2522	–	0.4973	0.0660	–	0.1113
	50–150	0.0022	0.4973	–	0.0000	0.1113	–
pF 2.5	0–25	–	0.9291	0.1495	–	0.9291	0.1495
	25–50	0.9291	–	0.0052	0.9291	–	0.0052
	50–150	0.1495	0.0052	–	0.1495	0.0052	–
pF 3.7	0–25	–	1.0000	0.0005	–	1.0000	0.0019
	25–50	1.0000	–	0.0001	1.0000	–	0.0003
	50–150	0.0005	0.0001	–	0.0019	0.0003	–
pF 4.2	0–25	–	1.0000	0.0004	–	1.0000	0.0190
	25–50	1.0000	–	0.0000	1.0000	–	0.0019
	50–150	0.0004	0.0000	–	0.0190	0.0019	–
GW	0–25	–	1.0000	0.0004	–	0.0149	0.0000
	25–50	1.0000	–	0.0008	0.0149	–	0.0960
	50–150	0.0004	0.0008	–	0.0000	0.0960	–
PAW	0–25	–	0.8056	0.3125	–	0.1984	0.6282
	25–50	0.8056	–	0.0111	0.1984	–	0.0022
	50–150	0.3125	0.0111	–	0.6282	0.0022	–
RAW	0–25	–	1.0000	0.2189	–	0.2419	0.1073
	25–50	1.0000	–	0.0196	0.2419	–	0.0001
	50–150	0.2189	0.0196	–	0.1073	0.0001	–
HAW	0–25	–	1.0000	1.0000	–	1.0000	0.8359
	25–50	1.0000	–	1.0000	1.0000	–	0.1949
	50–150	1.0000	1.0000	–	0.8359	0.1949	–

Red color means that the differences in values are statistically significant at the level of 0.05.

The highest SOM was recorded in the 0–25 cm layer, the medium in the 25–50 cm layer, and the lowest in the 50–150 cm layer, both in subsoiled and non-subsoiled soil (Tables 1–3, Fig. 5B). The SOM content in 0–25 cm layers was characterized by low variability (CV ≤ 15%), in 25–50 cm layers – large variability (CV ≥ 35%), and in 50–150 cm layers – medium (15% < CV ≤ 35%) and large variability (CV ≥ 35%) (Tables 1–3).

Considering the vertical soil profile before and after subsoiling, the SOM values in the lowest levels (50–150 cm) were approximately 70% lower compared to the first layer and about 60% lower compared to the second layer (Table 4, Fig. 5B). In the case of the subsoiled soil in the 0–25 cm layer, an increase of 1.7% was recorded, and in the 26–50 cm layer an increase of 5.3% was recorded concerning the non-subsoiled soil – in both cases these were insignificant increases (Table 4, Fig. 5B). Zhang et al. (2020) wrote that the soil has the potential to increase the SOM value and that subsoiling can activate this potential. As SOM increases, BD usually decreases and moisture content increases at pF 2.5, which positively affects PAW and RAW (Yang et al. 2024).

The maximum water capacity (MWC, at pF 0) in the subsoiled soil was higher than in the non-subsoiled soil by 10.6% in the first layer, 4.7% in the second layer, and 2.3% in the third layer (Tables 1–3, Fig. 5C). In each layer these differences were statistically significant (*P* < 0.05). The maximum water capacity in all layers of soil profiles showed small differences (CV ≤ 15%) (Tables 1–3). The MWC decreased with depth both in the soil before and after subsoiling (Fig. 5C). In the case of the non-subsoiled soil, moisture content at pF 0 was lower in the second layer than in the first layer by 3.3% (*P* > 0.05), in the third layer than in the second layer by 4.1% (*P* > 0.05) and as much as 7.3% (*P* < 0.05) in the third layer than in the first layer. After subsoiling it was lower by 8.4% (*P* > 0.05), 6.3% (*P* > 0.05), and 14.2% (*P* < 0.05), respectively (Table 4).

As a result of subsoiling, the highest, statistically significant (*P* < 0.05), an increase of field water capacity (FWC, at pF 2.5), amounting to 0.025 $m^3 \cdot m^{-3}$ (7.8%), was found in the second layer, the medium 0.018 $m^3 \cdot m^{-3}$ (5.7%) in the first layer and the lowest 0.006 $m^3 \cdot m^{-3}$ (1.9%) in the third layer (Tables 1–3, Fig. 5D). The retention corresponding to the FWC showed little variation (CV ≤ 15%), except for the first layer after deep tillage, where the coefficient of variation slightly exceeded 15% (Tables 1–3). The retention corresponding to FWC in the non-subsoiled soil reached the highest value in the 50–150 cm layer, while in the 0–25 cm and 25–50 cm layers, it was lower by 7.6% and 4.5%, respectively. After subsoiling, the highest value was found in the second layer, where this retention exceeded the values in the first and third layers by 5.4% and 1.0%, respectively (Table 4).

The results show that subsoiling increased soil moisture at pF 2.5 (Fig. 5D) and PAW (Fig. 5H) in the 0–25 cm layer by 5.7% and 8.2%, in the 25–50 cm layer by 7.8% and 9.3%, respectively, and in the 50–150 cm layer by 1.9% and 6.6%, respectively (Yang et al. 2024).

The retention corresponding to the boundary between RAW and HAW (at pF 3.7) in the non-subsoiled soil, similarly to the retention in case of the field water capacity, reached, on average, the highest value in the 50–150 cm layer, and in the 0–25 cm and 25– 50 cm layers it was lower by 20.0% and 22.4%, respectively (Tables 1–4, Fig. 5E). In the subsoiled soil, the highest value was also found in layer 50–150 cm, where this retention exceeded the values in the first and second layers by 18.2% and 21.7%, respectively. As a result of subsoiling, a slight (statistically insignificant (*P* > 0.05) increase of this retention occurred in the first layer. It amounted to 0.003 $m^3 \cdot m^{-3}$ (1.7%), while in the second and third layers, the differences did not exceed 0.5%. The retention corresponding to the boundary between water that is readily and hardly available to plants showed little variability (CV ≤ 15%), except for the third layer after subsoiling, where the coefficient of variation slightly exceeded 15% (Tables 1–3).

The retention at the permanent wilting point (at pF 4.2) was highest in the 50–150 cm layer where, in plowed soil, it exceeded the values of the first and second layers by 29.7% and 35.3%, respectively, and after subsoiling – by 22.6% and 23.8%, respectively (Tables 1–4, Fig. 5F). As a result of subsoiling, there was a slight increase in this retention, amounting to 0.002 $m^3 \cdot m^{-3}$ (1.8%) in the first layer and 0.006 $m^3 \cdot m^{-3}$ (5.2%) in the second layer, while in the third layer it decreased by 0.006 $m^3 \cdot m^{-3}$ (3.7%). These differences were statistically insignificant (*P* > 0.05) (Tables 1–3). The retention corresponding to the permanent wilting point showed low variability (CV ≤ 15%) in the first layer in the case of both types of cultivation and in the third layer of non-tilled soil. In comparison, in the second and third layers after deep tillage the variability was medium (15% < CV ≤ 35%) (Tables 1–3).

Gravitational water content (GW) in the 0–25 cm layer of subsoiled, was higher by 0.024 $m^3 \cdot m^{-3}$ (27.3%) than the value found in the non-subsoiled (Tables 1–3, Fig. 5G). In the 25–50 cm layer it was lower by 0.007 $m^3 \cdot m^{-3}$ (11.13%) after subsoiling, and in the 50–150 cm layer, it was higher by 0.002 $m^3 \cdot m^{-3}$ (6.4%). GW showed high variability (CV ≥ 35%) in the first and third layers of non-subsoiled soil and in the second layer of tilled soil, while in the remaining cases, variability was medium (15% < CV ≤ 35%) (Tables 1–3). GW decreased with depth both in the soil before and after subsoiling (Table 4, Fig. 5G). The highest values were recorded in the first layers, wherein the non-subsoiled soil it exceeded the values in the second and third layers by 36.5% and by 164.2%, and after subsoiling by 95.4% and by 216.2%, respectively. In the non-subsoiled soil, significant differences occurred between the first-third and second-third layers ($P < 0.05$), whereas in the subsoiled soil, between the first-second and first-third layers (Table 4).

In all layers, higher values of total PAW in tilled soil were recorded (Tables 1–3, Fig. 5H). The highest, statistically significant ($P < 0.05$) increase was 0.019 $m^3 \cdot m^{-3}$ (9.3%) in the second layer (Wang et al. 2019), slightly lower – 0.016 $m^3 \cdot m^{-3}$ (8.2%) in the first layer and the lowest – 0.012 $m^3 \cdot m^{-3}$ (6.8%) in the third layer. PAW showed low variability (CV ≤ 15%), except for the first and third layers of non-tilled soil where it was classified as medium (15% < CV ≤ 35%).

Before subsoiling, the PAW increased in the second layer compared to the first by 8.1% ($P > 0.05$), then in the third layer, it decreased by 12.6% and 5.5% compared to the second ($P < 0.05$) and the first layer ($P > 0.05$) (Table 4). After subsoiling, an increase of 9.2% of PAW was observed in the second layer compared to the first one ($P > 0.05$), followed by a decrease of 14.6% in the third layer and by 6.7% compared to the second one ($P < 0.05$) and the first one ($P > 0.05$) (Table 4). Similar results were obtained by Wang B. et al. (2024), where subsoiling increased the level of water storage, which was of great importance in dry years and had a beneficial effect on crop yields.

The total plant available water (PAW) includes readily available water (RAW) and hardly available water (HAW). In all studied soil layers, after subsoiling, an increase in RAW was found (Tables 1–3, Fig. 5I). The average increase was 0.015 $m^3 \cdot m^{-3}$ (10.1%) in the 0–25 cm layer, 0.024 $m^3 \cdot m^{-3}$ (14.7%) in the 25–50 cm layer and 0.007 $m^3 \cdot m^{-3}$ (5.3%) in the 50–150 cm layer and only the highest increase in the second layer was statistically significant ($P < 0.05$). In the case of HAW, after subsoiling, an increase by only 1% was recorded for the first layer, a decrease by 0.005 $m^3 \cdot m^{-3}$ (13.8%) was recorded for the second layer, and a further increase by 0.005 $m^3 \cdot m^{-3}$ (11.6%) was recorded for the third layer (Table 4, Fig. 5J). RAW was characterized by average variability in the first and third layer of both types of cultivation (15% < CV ≤ 35%) and low variability in the second layer. Coefficients of variability of HAW in all layers of soil profiles confirm its high variability (CV ≥ 35%) (Tables 1–3).

The analysis of the obtained results showed that the consequence of soil subsoiling was an increase in the values of most of the analyzed hydrophysical properties of soil, only in the case of GW and HAW in the 25–50 cm layer and retention at pF 3.7 and pF 4.2 in the 50–150 cm layer, lower values were observed after subsoiling (Tables 1–3). The highest increase in GW was found in the 0–25 cm layer, and total PAW and RAW – in the 25–50 cm layer (Fig. 5H, I).

This research and analysis confirm the positive effect of subsoiling on the water storage capacity in the soil profile, especially in subsoil layers, as also indicated by other researchers (Jiao et al. 2017, Wang et al. 2019, Wu et al. 2020). This positively affects agriculture because vegetation has access to soil water for longer without rainfall.

The whole 150 cm profile of plowed soil, when saturated to full water capacity, can accumulate 347 mm, i.e. 3470 $Mg \cdot ha^{-1}$ of water, while after subsoiling it can absorb 374 mm, i.e., 3740 $Mg \cdot ha^{-1}$, which causes an increase in retention by 27 mm, i.e., 270 $Mg \cdot ha^{-1}$ (7.8%). The total PAW increases by 20.7 mm, i.e., 207 $Mg \cdot ha^{-1}$ (7.5%). From an agricultural point of view, the most important resource is the retention within the range of pF 2.5 to pF 3.7 (RAW). As a result of subsoiling, this retention increased by 17.1 mm, i.e., 171 $Mg \cdot ha^{-1}$ (7.9%). The lowest increase was found within the range from pF 3.7 to pF 4.2 (HAW), which was 3.6 mm, i.e. 36 $Mg \cdot ha^{-1}$ (5.9%).

The increase in water storage in the soil profile after subsoiling was also observed in the experiment of Sun et al. (2013) and Yang et al. (2021b), which was important for maize and wheat cultivation.

CONCLUSION

Water is an essential factor for the life of all organisms and it is also a fundamental component of the plant's environment. Providing appropriate conditions for the growth and development of crops can be achieved by using subsoiling, which, as our own and other studies show, reduces or eliminates excessive soil compaction and improves water storage in the soil.

The subsoiling of silty loam soils (SiL) resulted in a decrease in bulk density and an increase in total porosity in each profile layer. The most prominent changes occurred in the upper layer, medium in the middle layer, and the slightest in the lower layer, which is outside the direct range of influence of the subsoiler.

The highest SOM content was recorded in the 0–25 cm layer, the medium in the 26–50 cm layer and the lowest in the 51–150 cm layer, both in tilled and non-tilled soil.

Subsoiling increased the maximum and field water capacity in each profile layer. However, in the case of maximum capacity, it was statistically significant in each layer and only in the second layer in the case of field capacity.

Subsoiling resulted in a slight, statistically insignificant increase in retention corresponding to the boundary of water that is easily/readily and hardly available to plants and the permanent wilting point in the first and second layers, while in the third layer there was a slight decrease in these retentions.

Subsoiling has not caused any significant changes in the amount of gravitational water and water hardly available to plants. On the other hand, in all layers of the profiles, higher values of total plant available water and readily/easily available water were recorded in the tilled soil, however, only in the second layer were these increases statistically significant.

Due to subsoiling, the 150 cm soil profile can accumulate by 270 $Mg \cdot ha^{-1}$ (7.8%) more water at full water capacity. Of which the increase in total plant available water is 207 $Mg \cdot ha^{-1}$, of which 171 $Mg \cdot ha^{-1}$ is easily available water, and 36 $Mg \cdot ha^{-1}$ is hardly available water.

The influence of subsoiling on increasing the use of potential retention capacity of arable soils was much greater in upper layers than in the layer outside the working range of the subsoiler.

The results of the study have shown that subsoiling of compacted heavy arable soils is justified because it contributes to their retention level which, with the water deficit resulting from the observed climate change, is a measure that improves air-water relations in the soil profile and rational management of water resources in the agricultural space.

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