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SUBSOILING EFFECTS ON HYDRO-PHYSICAL QUALITY INDICATORS IN A SILTY LOAM SOILS IN SOUTHERN POLAND

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Abstract. One of the factors affecting the sustainable soil water management is agricultural activity, which leads to a change in the soil hydro-physical parameters through land use. The benefits of subsoiling silty loam soils are extant in the literature, but detailed studies of subsoiling effects on soil hydro-physical quality (SHPQ) are limited. The field experiments were conducted on arable land in two regions of southern Poland: i) the Racibórz County (5 measuring points) and ii) the Krakow County (3 measuring points) from 2012 to 2015, to study the effect of subsoiling to a depth of 0.50 m and conventional tillage on the SHPQ. For each of the selected measuring points undisturbed and disturbed soil sampling were taken. The SHPQ parameters included bulk density (BD), total organic carbon content (TOC), air capacity (AC), plant-available water capacity (PAW), relative field capacity (RFC), structural stability index (StI), the Dexter's index of soil physical quality (S) and saturated hydraulic conductivity (Ks), which was obtained from *in-situ* measured. Statistical analyses showed two main groups of SHPQ indicators, of which the most sensitive on soil subsoiling were the BD and Ks values. In general, after soil subsoiling significantly decreased ($P<0.05$) of the BD values was observed in topsoil and subsoil layers, and additionally significantly increased of the S index and Ks values but only in surface layers of soil.

Key words: soil quality; soil degradation; subsoiling; soil and water management; sustainable agriculture; climate change;

1. INTRODUCTION

It is generally recognized that the soil is a non-renewable natural resource. Most crops need at least 10–15 cm of healthy soil to grow well. In fact, one cm of soil can take 200–500 years to form (Schoonover & Crim 2015; Ateh et al., 2016).

Currently, reduction of the total area of arable lands are observed. This trend is particularly noticeable in the European Union (EU), including in Poland. Silt soils are fertile and have susceptibility to shrinking and swelling. Dependent on land cultivation and agricultural practices the soil hydraulic and physical properties are widely associated with the soil compaction, water movement into the soil profile and water and air relations (Cameira et al., 2003; Pagliai et al., 2004; Hakl et al., 2007; Nawaz et al., 2013; Kahlon & Khurana, 2017). Soil compaction is one form of physical degradation it can make changes the soil structure, water and air relationship, porosity as well as to influence rooting plants (Hakl et al., 2007; Nawaz et al., 2013). To cope with soil compaction farmers using subsoiling (deep loosening of soil) and this way can alleviate high soil compaction, increase soil water storage, facilitate deeper rooting, and improve the availability of subsoil resources to crops (Varsa et al., 1997; Liu et al., 2016; Schneider et al., 2017; Feng et al., 2018; Borek et al., 2018). Subsoiling is an important agricultural treatment for improving yield on a loess soil, especially in a dry year (Jin et al., 2017; Sun et al., 2017; Liang et al., 2019). However, this method of soil cultivation is owned by a laborious and expensive process (Getahun et al., 2018). To date, establishment of soil hydro-physical quality (SHPQ) criteria based on subsoiling is difficult due to limited of literature data.

From an agricultural-environmental point of view, the soil as the Earth's surface, is a natural medium for growth and development of the plants. A key role in the production the appropriate quality and quantity of the crop have a SHPQ (Karlen et al., 1997;

Arshad & Martin 2001; Dexter, 2004a; Dexter, 2004b; Reynolds et al., 2009; Paluszek, 2011; Borek, 2019), which according to Paluszek (2011) SHPQ can be defined as physical and water properties of soil enabling to function in natural or agro- ecosystems, contributing to obtaining a high quality and quantity crops yields and to ensure food security in Europe and around the world. Technical and technological progress that we now see on a global scale also applies to the agricultural sector. Modern agriculture should take into account the principle of sustainable development. There are many concepts of sustainable agriculture in literature (Velten et al., 2015). According to Schaller (1993) the sustainable agriculture relies on more careful and efficient farming with sensitive technologies, which they will be able to eliminate many undesirable effects of conventional agriculture. Sustainable agriculture depends largely on soil quality (Moebius et al., 2007).

The soil physical quality concept and the calculation methods are cited in the work of Dexter (2004a, 2004b), Reynolds et al. (2008; 2009) and Paluszek (2011, 2013). The most well-known and widely used indicator is dry bulk density of soil (BD) (Reynolds et al., 2009; Hakl et al., 2007; Nawaz et al., 2013; Reynolds et al., 2008). This physical parameter is often used as indicator of soil compaction, aeration, strength, and ability to store and transmit water. Soils with unfavourable air and water ratio can affect both quantity and quality of yields, so soil air capacity (AC) is very important indicator in sustainable agriculture (Ferreyra et al., 2011). From an agricultural point of view, the plant-available water capacity (PAW) is very important soil hydraulic indicator (Reynolds et al., 2009) used to direct determination of available water for plants during growing season. Total organic carbon (TOC) play a key role in the chemical and biological quality of soil and has direct effects on soil structure and therefore also on crop production, aeration and water infiltration into soil profile (Muršec et al., 2018), which can be determined by soil structural stability index (StI) (Pieri, 1992). To evaluate soil physical quality Dexter proposed the use the synthetic indicator (S index) based on soil water retention curve (SWRC) (Dexter, 2004a; Dexter, 2004b). The soil's ability to retain water and air relative to the total pore volume is defined by Reynolds et al., (2008) as relative field capacity (RFC). A very important hydro-physical property of soils is saturated hydraulic conductivity (Ks). The Ks is one of the most important physical parameter of soil, especially when it comes to modeling water flow in a porous medium, designing devices for soil irrigation and drainage, shaping surface runoff and water erosion, as well as in agricultural cultivation and environmental processes occurring in the soil profile (Kanso et al., 2018; Ottoni et al., 2019).

The objective of this study was to investigate the effect of subsoiling on hydro-physical quality indicators of silty loam soils in two agriculture sites located in the south of Poland.

2. MATERIAL AND METHODS

2.1. Study area

The study was carried out in southern Poland (Fig. 1A) at two representative sites: i) Wojnowice, Strzybnik and Owsiszcze objects: located near Racibórz city in the southern region of the Silesian state (Fig. 1B); ii) Prusy object: located near Kraków city in the northern region of the Małoposkie state (Fig. 1C). Both are currently the most important regions for cereals and vegetables expansion in Poland. According to the Polish Soil Classification (2011), WRB (2014) and USDA soil taxonomy (ST) (1999), examined soils were classified as: Order 3. Brown forest soils (Brown earths, Polish: Gleby brunatnoziemne; WRB: Cambisols; ST: Inceptisols - Udepts) in Strzybnik and Prusy; Order 5. Brown forest podzolic soils (Soil lessivé) (Polish: Gleby płowoziemne; WRB: Luvisols, Albeluvisols; ST: Alfisols - Aqualfs, Udalfs) in Wojnowice and Owsiszcze; Order 7. Chernozemic soils (Polish: Gleby czarnoziemne; WRB: Chernozems, Phaeozems; ST: Mollisols - Aquolls, Udolls) in Prusy.

The mean altitude of the Prusy object is between 252.0 to 266.5 m a.s.l., whereas the mean height of the Wojnowice, Strzybnik and Owsiszcze objects is between 215.0 to 260.5 m a.s.l.. According to the geographical division by Kondracki (2011), the object Prusy is situated in the Polish Upland province (31), in the macroregion of the Niecka Nidziańska (342.2) and in the mesoregion of the Proszowice Plateau (342.23), whereas the Wojnowice, Strzybnik and Owsiszcze objects are situated in the Central European Lowlands province (31), in the macroregion of the Silesian Lowlands (318.5) and in the two mesoregions: the Głupczyce Plateau (318.58) and the Raciborska Basin (318.59).

2.2. Meteorological Conditions

The meteorological conditions of the study sites are presented in Table 1 and Table 2. The climate of Poland is described as moderate transient, which means that mixing of air masses between oceanic climate dominating in the north and west of the country, and continental climate in the south and east (Kundzewicz et al., 2017).

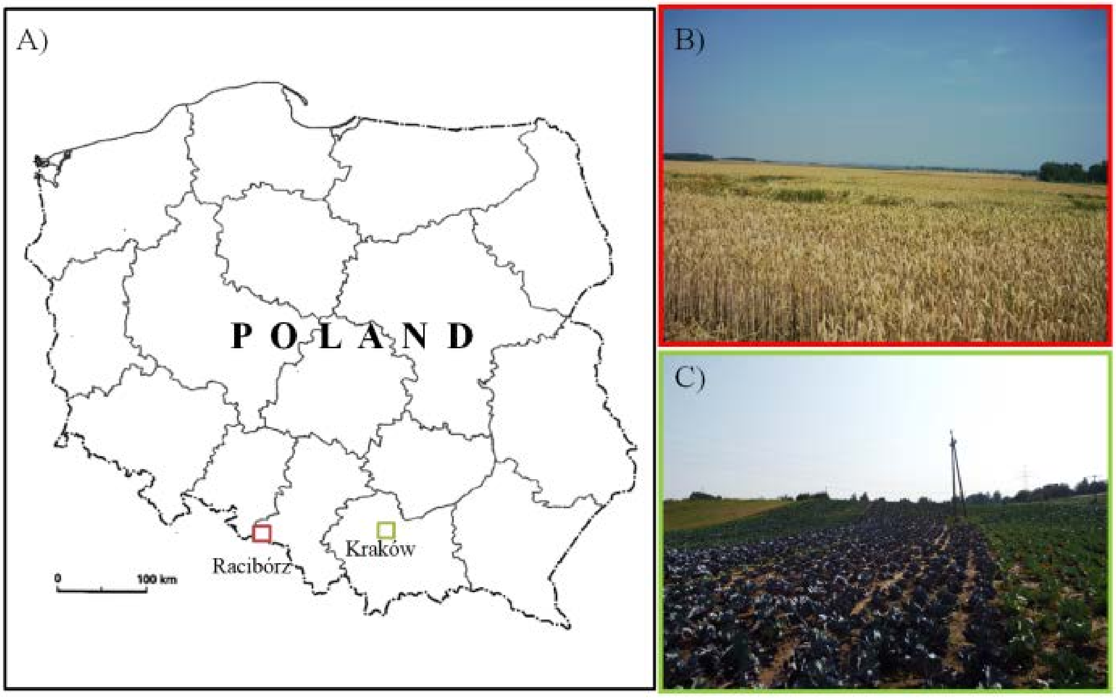

Figure 1. Location of study areas on the map of Poland (A); the Racibórz object (B) and the Prusy object (C).

In terms of climate the study areas are considered the warmest areas in this region. Such a distribution of precipitation and air temperature causes that a dry periods and water shortages may occur during growing season (Ziernicka-Wojtaszek & Krużel, 2016). On the other hand, Stefanidis & Chatzichristaki (2017) reported that less rainfall means less soil erosion in sculptured area.

2.3. Field experiment and field tests

In the field experiment, a 7-tines passive subsoiler from Maschio was used in Wojnowice, Strzybnik and Owsiszcze, while a 3-tines passive subsoiler was used in Prusy. The effective operating depth of the working elements of the two subsoilers was the same i.e. 50 cm, and each of the tines/coulters were spaced of 50 cm. The dates when the study and subsoiling treatment were performed are given in Table 3.

At each sampling point, small soil pits were opened to collect disturbed and undisturbed soil samples from top- and subsoil (0–25 and 25–50 cm).

In–situ, at a depth of 0–25 cm (topsoil) and 25–50 cm (subsoil), the soil saturated hydraulic conductivity (Ks) was measured using double-ring infiltrometer (DRI) metod. The DRI consists of an inner ring of 9.5 cm diameter and an outer ring of 19.5 cm diameter inserted into the ground at 10 cm depth by using falling weight type hammer strikingon a wooden

Table 1. Precipitation totals in study years as against multiannual (1971–2000)*.

Year / period	Months												Sum Jan–Dec
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
precipitation totals [mm] for the Racibórz meteorological station													
2012	41	24	18	41	35	75	89	69	58	81	37	18	586
2013	44	29	36	21	132	110	14	48	99	24	31	9	597
2014	21	16	23	27	137	75	58	92	127	35	18	16	645
1971–2000	28	26	32	45	67	79	94	74	56	41	40	34	616
precipitation totals [mm] for the Kraków meteorological station													
2013	59	25	41	12	87	184	27	21	86	14	67	21	644
2014	38	18	31	39	110	64	77	91	67	32	35	24	626
2015	49	26	41	33	102	36	42	68	68	26	56	5	551
1971–2000	35	30	35	50	74	94	81	76	60	50	40	38	663

*acc. to IMGW – Institute of Meteorology and Water Management

Table 2. Mean air temperatures in study years as against multiannual (1971–2000)*.

Year / period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean Jan–Dec
Mean air temperature [ºC] for the Racibórz meteorological station													
2012	-0.3	-5.6	5.4	9.9	15.3	17.7	19.9	19.1	14.7	9.0	6.5	-1.1	9.2
2013	-2.2	-0.2	0.1	9.0	13.8	16.9	19.7	19.1	12.6	10.8	5.5	2.7	9.0
2014	0.6	4.0	6.9	10.8	13.8	16.3	20.4	17.4	15.6	11.1	7.1	1.6	10.5
1971–2000	-1.3	-0.2	3.8	8.2	13.5	16.1	17.8	17.7	13.6	9.0	3.6	0.2	8.5
Mean air temperature [ºC] for the Kraków meteorological station													
2013	-2.4	-0.5	-0.9	8.9	14.3	17.5	19.6	19.1	12.1	10.1	4.9	1.3	8.7
2014	-1.2	2.2	6.6	10.3	13.9	16.3	20.4	17.5	15.1	9.6	6.0	1.1	9.8
2015	1.1	0.6	4.7	8.8	13.1	17.6	20.6	21.5	15.1	7.7	5.4	4.0	10.0
1971–2000	-2.3	-0.9	3.1	8.0	13.4	16.2	17.8	17.5	13.2	8.4	2.8	-0.6	8.1

* acc. to IMGW – Institute of Meteorology and Water Management

Table 3. Dates of field tests.

Date of the:	Name of the test objects			
	Wojnowice	**Strzybnik**	**Owsiszcze**	**Prusy**
study in the no subsoiling field	Jun 2012	Jun 2012	Jul 2014	Apr 2011/Apr 2015
subsoiling treatment	Oct 2011	Oct 2011	Sep 2014	Sep 2014
study in the subsoiling field	Jun 2012	Jun 2012	Oct 2014	Oct 2014/Apr 2015

plank placed on top of ring uniformly without or undue disturbance to soil surface. Each ring of the infiltrometer was filled up with a constant head of water level and the outher ring helps to check the lateral flow from the inside ring which can estimate better Ks reducing losses. The Ks can be estimated when water flow rate inside the inner ring comes to a steady state (Islam et al., 2017), which in the case of the studied soils lasted about 3 hours.

2.4. Laboratory Analysis

In the laboratory, the particle size distribution of examined soils were determined on the based on disturbed soil samples using the Bouyoucose–Casagrande areometric method modified by Prószyński (PN–R–04032:1998). The contents of main fractions of soil, such as: sand (2.0–0.05 mm), silt (0.05–0.002 mm) and clay (< 0.002 mm) were determined according to the USDA classification (1999). The BD was calculated by the gravimetric method in Kopecky's cylinders. The total organic carbon content (TOC) was calculated by Tiurin's method from disturbed soil samples and passed through the sieve a 0.25 mm (Ostrowska et al., 1991). The total plant-available water capacity (PAW) was determined as difference between the moisture retained at at −33 kPa representing field capacity (FC, pF 2.5) and −1500 kPa representing the permanent wilting point (PWP, pF 4.2) using set for pF determination with ceramic plates in the 5 and 15 bar pressure plate extractor. The pressure plate equipment used in this study is made by American Soil Moisture Equipment Corporation. In engineering practice, soil suction has usually been calculated in pF units (Schofield, 1935).

2.5. Review of Selected Soil Hydro-Physical Quality Indicators

Used in this paper SHPQ indicators with equations (Eq. 1–8) and ranges/classes of soil quality are presented in Table 4.

2.6. Statistical Analysis

All data sets obtained before and after subsoiling were submitted to descriptive statistics (mean, median, standard deviation, coefficient of variation, and maximum and minimum values) and to the Shapiro-Wilk test, at the 5% significance level, to check the normality of each data distribution. To determine the overall effect of subsoiling on all data sets, paired t tests were performed (Montgomery et al., 2003). For normal data distributions, the hypothesis of the applied test was parametric (t statistics), and for non-normal distributions, the test was nonparametric (Wilcoxon test). The coefficient of variation (CV) of each data set was classified according to Wilding & Drees (1983): $CV \leq 15\%$ – low variability of the data set around their mean; $15\% < CV \leq 35\%$ – moderate variability; and

Table 4. Characteristics of selected SHPQ indicators with calculation equations and ranges.

Bulk density (BD):

$$BD = \frac{M}{V} (Mg \cdot m^{-3}) \quad (1)$$

Where: M – the mass of dry soil wight (Mg); V – the soil volume (m^3).
BD < 1.30 $Mg \cdot m^{-3}$ – ideal for SiL (USDA, 1999); BD ~ 1.60 $Mg \cdot m^{-3}$ – marginal; BD>1.75 $Mg \cdot m^{-3}$ – restrictive (Reynolds et al., 2009; Drewry et al., 2008).

Air capacity (AC):

$$AC = \theta_s - \theta_{FC} \ (m^3 \cdot m^{-3}) \quad (2)$$

where: θ_s – the saturated volumetric water content or soil porosity ($m^3 \cdot m^{-3}$); θ_{FC} – the volumetric water content corresponding to the field capacity at pF = 2.5 ($m^3 \cdot m^{-3}$).
AC > 0.10 $m^3 \cdot m^{-3}$ – ideal for arable soils (Reynolds et al. 2009)

Plant-available water capacity (PAW):

$$PAW = \theta_{FC} - \theta_{PWP} \ (m^3 \cdot m^{-3}) \quad (3)$$

where: θ_{FC} – field capacity at pF 2.5 ($m^3 \cdot m^{-3}$), θ_{PWP} – the permanent wilting point water content at pF 4.2 ($m^3 \cdot m^{-3}$).
PAW ≥ 0.20 $m^3 \cdot m^{-3}$ – ideal; 0.15 ≤ PAW < 0.20 $m^3 \cdot m^{-3}$ – good 0.10 ≤ PAW < 0.15 $m^3 \cdot m^{-3}$ – limited; PAW < 0.10 $m^3 \cdot m^{-3}$ – poor (Reynolds et al., 2009).

Relative field capacity (RFC):

$$RFC = \frac{\theta_{FC}}{\theta_S} \ (–) \quad (4)$$

where: θ_{FC} – field capacity at pF 2.5 ($m^3 \cdot m^{-3}$); θ_s – saturated volumetric water content at pF 0 ($m^3 \cdot m^{-3}$).
0.6 ≤ RFC ≤ 0.7 – optimal; RFC < 0.6 – limited water; RFC > 0.7 – limited aeration (Reynolds et al. 2009).

Soil structural stability index (StI):

$$StI = \frac{1.724 \cdot TOC}{(silt + clay)} \cdot 100 \ (\%) \quad (5)$$

where: TOC – the soil total organic carbon content (%); clay + silt – the soil's combined clay and silt content (%).
StI < 5% structurally degraded soil 5% < StI < 7% high risk of soil structural degradation; 7% < StI < 9% low risk of soil structural degradation; StI > 9% indicates sufficient TOC to maintain the structural stability (Pieri, 1992; Reynolds et al. 2009).

Total organic carbon (TOC):

$$TOC = \frac{(M_1 - M_2) \cdot n \cdot 0.003}{a} \cdot 100 \ (\%) \quad (6)$$

where: M_1 and M_2 – volume of Mohr salt used for titration of the control and soil samples, respectively (cm^3); n – titer of Mohr's salt solution; 0.003 – milligram carbon equivalent; a – weight of soil sample (g); 100 – percentage conversion.
TOC within range 3–5% is optimal for arable soils (Reynolds et al. 2009).

S index by Dexter:

$$S = -n(\theta_{sat} - \theta_{res}) \left[\frac{2n-1}{n-1}\right]^{\left(\frac{1}{n} - 2\right)} \ (–) \quad (7)$$

where: θ_{sat} and θ_{res} – saturated and residual water contents in gravimetric units ($kg \cdot kg^{-1}$); n – the shape parameter of soil water characteristic (from RETC).
S ≥ 0.050 – very good soil quality; 0.035 ≤ S < 0.050 – good; 0.020 ≤ S < 0.035 – poor; S < 0.020 – very poor or degraded physical quality (Van Genuchten, 1980; Dexter, 2004a and 2004b; Castellini et al., 2013).

Soil saturated hydraulic conductivity (Ks):

$$K_s = -\frac{Q \cdot L}{\Delta H \cdot A} \ (m \cdot day^{-1}) \quad (8)$$

where: Q – the rate of flow ($m^3 \cdot day^{-1}$); L – the length of the specimen (m); A – the cross section area of specimen (m^2); ΔH – the constant hydraulic head causing flow (m) (Darcy, 1856).
optimal Ks values for agriculture soils within the range 0.5–5 $m \cdot day^{-1}$ to promote a rapid infiltration and redistribution of plant available water (Reynolds et al., 2009)

CV > 35% – high variability. Further, a Spearman correlation test was conducted to evaluate the effect of subsoiling on the relationship between each pair of variables. The strength of the correlation was assessment using the following range: 0.00–0.19 "very weak correlation", 0.20–0.39 "weak", 0.40–0.59 "moderate" 0.60–0.79 "strong" and 0.80–1.0 "very strong". Cluster analysis was performed using Euclidean distance and the Ward's method to identify similar groups of indicators before and after subsoiling. These analyses were performed using the statistical package Statistica PL (version 12.5) with a 5% significance level.

3. RESULTS AND DISCUSSION

According to USDA (1999) soil texture classification system (Fig. 2) and particle-size analysis of soil, 100% of the samples were silt soils. All samples were characterized as silty loam (100%) with an average content of 20% sand, 67% silt, and 13% clay. In generally, soil particle-size distribution, is one of the most important soil physical properties, and have great importance to soil hydro-physical quality (Hu et al., 2011). The high silt content is characteristics to a loess soils, which are among the most fertile in the world, principally because the abundance of silt particles ensures a good air and water relationship in soil profile (Catt, 2001).

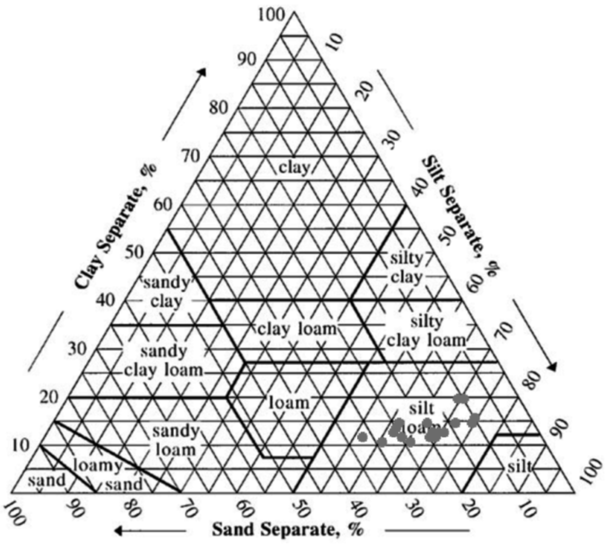

Figure 2. Distribution of soil samples in the USDA textural triangle.

Basic descriptive statistics and probabilities (P) of the paired t test or Wilcoxon test for selected SHPQ indicators are shown in Table 5 and Table 6. The mean and median values of all evaluated data sets were altered due to the intense soil disturbance of the topsoil (0–25 cm) and the subsoil (25–50 cm) during to the subsoiling treatment. Among the analyzed properties, the most frequently estimated as ideal or good/optimal were the following: soil bulk density, plant available water content, S index and the saturated hydraulic conductivity (Table 5 and 6; Fig. 3). Those indicators were also sensitive to changes in soil structure due to subsoiling (Peixoto et al., 2019). Both before and after subsoiling the high variability CV were observed in Ks and the low variability in BD values. The most significantly altered indicators ($P < 0.05$) were observed BD, S and Ks in top layers of examined soils and BD in sub layers of soil (Table 5 and 6). Subsoiling contributed to a decrease of the mean values of soil compaction (BD) in the topsoil and in the subsoil of 7.0% and 3.1%, respectively (Table 5 and 6; Fig. 3A). Soil compaction increased with depth. Other results showed that soil compaction has an adverse effect on some hydro-physical properties, which have an adverse effect on quantity and quality of yields as well as water and nutrient use efficiencies by crops (Ishaq et al., 2001; Mari et al., 2008). Schneider et al., (2017) and Feng et al., (2018) observed that deep tillage of soil without furrow inverts influence on decrease of bulk density. In consequence, the farmers are saving energy and tend to reduce production costs. Abu-Hamdeh (2003) based on the results of its investigation, reported that subsoiling is a method to alleviate or reduce effects of soil compaction. Sun et al. (2017) reported that subsoiling could affecting the root system distribution and could create favourable conditions for root growth. Botta et al., (2006) and Liu et al., (2016) informed that the soil re-compaction is visible again after just 2 years. Therefore, the subsoiling procedure should be re-implemented. According to Ma et al., (2015) soil loosened improves water retention capacity, especially in subsoil layers and significantly decreased soil moisture content in topsoil layers. Abidela Hussein et al., (2019) noticed that the posttreatment bulk density of subsoiling was significantly less than in the traditional tillage systems, which plays an important role on fields with plenty of tramlines.

The mean values of AC were very low in all layers the soils in the traditional cultivation, ranging from 0.079 $m^3 \cdot m^{-3}$ in top soil to 0.071 $m^3 \cdot m^{-3}$ in sub soil (Table 5 and 6; Fig. 3B). However, after subsoiling recorded the highest mean value of AC (0.104 $m^3 \cdot m^{-3}$), but only in top soil, which was already very close to the critical limit. The effects of soil loosening on AC is visible in this study and a similar situation was observed by Lozano et al., (2016).

The mean values of PAW ranged from 0.218 $m^3 \cdot m^{-3}$ in top soil layers to 0.222 $m^3 \cdot m^{-3}$ in sub soil layers under traditional cultivation. The subsoiling leds to a decrease of approximately 5% of the PAW (Table 5 and 6; Fig. 3C), associated with partial drainage of wet soil (Bogdał et al., 2016). In both cases, the PAW values showed that silty loam soils are ideal (>0.20 $m^3 \cdot m^{-3}$) for maximum root growth and function.

The RFC values were poor and higher than the upper limit of the optimal interval (RFC = 0.7) for both layers – whether before or after the subsoiling (Table 5 and 6; Fig. 3D). Investigated soils are insufficient aerated to ensure appropriate amount of air in root zone and demonstrate poor ability to rapid

Table 5. Basic descriptive statistics and probabilities (P) of the *paired t test* (t) or *Wilcoxon test* (W) for selected SHPQ indicators for layers of 0–25 cm before (T) and after (S) subsoiling.

SHPQ Index	Unit		n	Min.	Max.	Mean	Median	SD	CV (%)	P
BD	$Mg \cdot m^{-3}$	T	20	1.48	1.70	1.57	1.55	0.06	3.78	**0.0001^{t}**
		S	20	1.32	1.63	1.46	1.45	0.09	6.08	
AC	$m^3 \cdot m^{-3}$	T	19	0.014	0.219	0.079	0.069	0.05	65.65	0.0949^{W}
		S	19	0.026	0.202	0.104	0.107	0.05	45.99	
PAW	$m^3 \cdot m^{-3}$	T	19	0.160	0.283	0.218	0.214	0.04	16.76	0.2173^{t}
		S	19	0.160	0.275	0.215	0.204	0.04	17.73	
RFC	–	T	19	0.470	0.960	0.805	0.840	0.13	15.62	0.3981^{W}
		S	19	0.600	0.960	0.776	0.750	0.11	13.68	
TOC	%	T	16	0.36	1.05	0.64	0.61	0.16	25.70	0.2001^{t}
		S	16	0.36	1.05	0.64	0.62	0.16	25.52	
StI	%	T	16	0.73	2.12	1.42	1.45	0.37	25.80	0.2106^{t}
		S	16	0.73	2.12	1.45	1.45	0.39	26.71	
S	–	T	16	0.052	0.080	0.067	0.067	0.01	9.53	**0.0157^{W}**
		S	16	0.048	0.101	0.078	0.082	0.02	21.41	
Ks	$m \cdot day^{-1}$	T	16	0.07	1.62	0.50	0.38	0.46	91.27	**0.0006^{W}**
		S	16	0.61	6.26	2.40	1.63	1.72	71.54	

Note: **bold** type indicates significant correlations at $P < 0.05$

Table 6. Basic descriptive statistics and probabilities (P) of the *paired t test* (t) or *Wilcoxon test* (W) for selected soil SHPQ indicators for layers of 25–50 cm before (T) and after (S) subsoiling.

SHPQ Index	Unit		n	Min.	Max.	Mean	Median	SD	CV (%)	P
BD	$Mg \cdot m^{-3}$	T	20	1.53	1.70	1.60	1.60	0.06	3.64	**0.0003^{t}**
		S	20	1.45	1.65	1.55	1.56	0.06	3.80	
AC	$m^3 \cdot m^{-3}$	T	19	0.034	0.142	0.071	0.059	0.03	42.76	0.5461^{W}
		S	19	0.031	0.148	0.075	0.071	0.04	49.01	
PAW	$m^3 \cdot m^{-3}$	T	19	0.134	0.287	0.222	0.235	0.04	16.95	0.1158^{W}
		S	19	0.134	0.250	0.216	0.231	0.04	17.13	
RFC	–	T	19	0.700	0.920	0.824	0.840	0.06	7.53	0.6026^{W}
		S	19	0.680	0.920	0.825	0.830	0.08	9.16	
TOC	%	T	16	0.14	0.68	0.32	0.25	0.16	50.39	0.2757^{t}
		S	16	0.11	0.68	0.34	0.34	0.16	48.48	
StI	%	T	16	0.26	1.47	0.68	0.52	0.36	52.78	0.2524^{t}
		S	16	0.21	1.47	0.71	0.72	0.36	50.71	
S	–	T	16	0.032	0.080	0.063	0.062	0.01	20.42	0.1213^{W}
		S	16	0.053	0.081	0.066	0.067	0.01	8.95	
Ks	$m \cdot day^{-1}$	T	16	0.07	3.99	0.87	0.50	1.03	118.32	0.0557^{W}
		S	16	0.16	8.99	1.69	1.03	2.32	137.43	

Note: **bold** type indicates significant correlations at $P < 0.05$

drainage of excess soil water (Reynolds et al., 2003), which can lead to the onset of anaerobic conditions in soil profile for most of the growing season (Olness et al., 1998). In this study after subsoiling the RFC values were decreased but not significant.

The TOC (< 3%) and StI (< 5%) indicates a structurally degraded soil (Table 5 and 6; Fig. 3E and 3F). Shahab et al. (2013) reported that relatively high organic carbon contents could improve pore size distribution and finally affect on water storage. How important is the organic materials in soil to increase water retention in rural areas, especially in light soils, informed Şeker & Manirakiza, (2020).

The obtained S index values of all soils under study show a very good hydro-physical conditions (Table 5 and 6; Fig. 3G). In general, the silt loam soils ("loess soils") are characterized by a good ability water retention (Paluszek, 2013). Dynamic SHPQ indicators such as Ks and AC were affected by the subsoiling. However, static SHPQ indicators such as

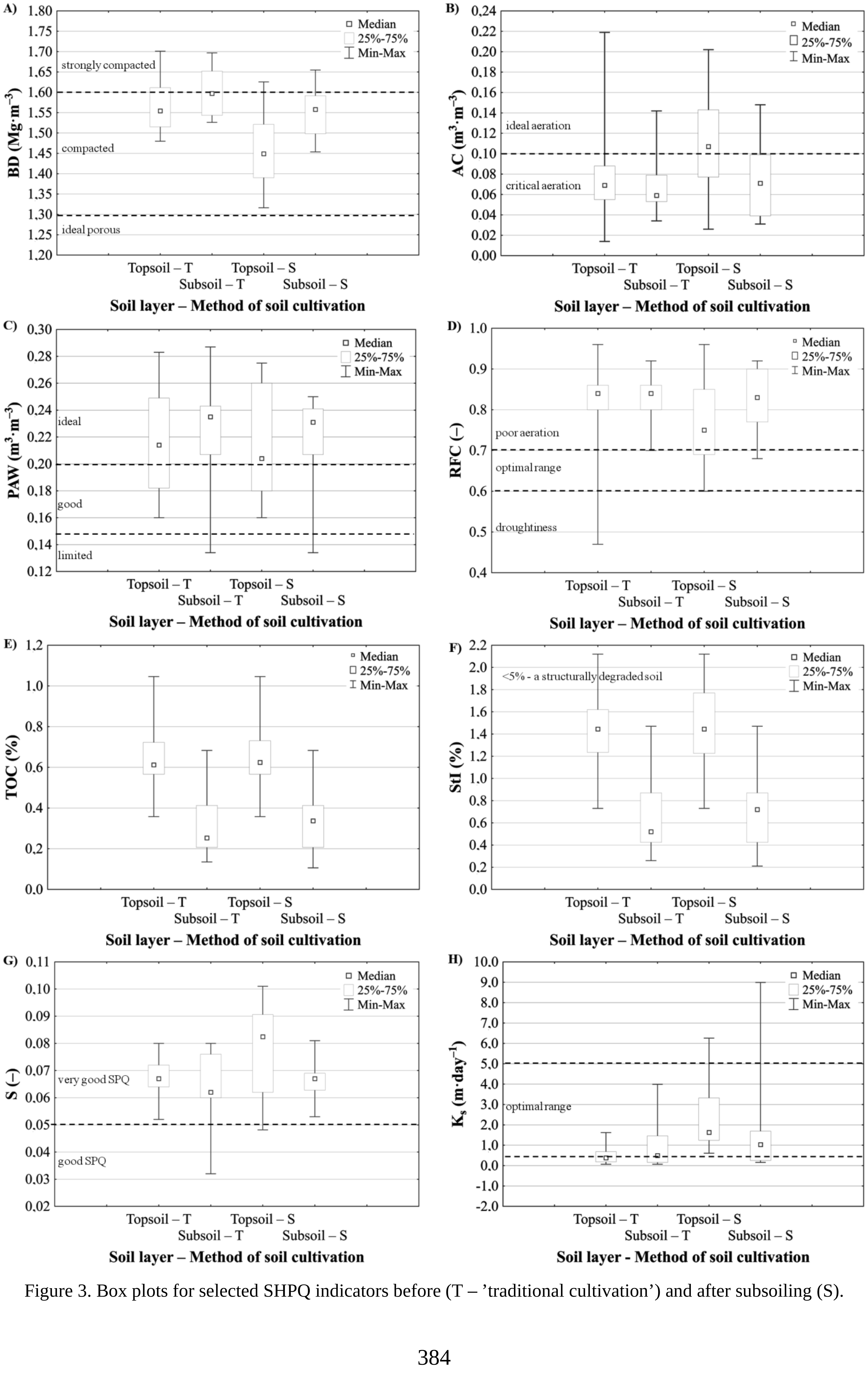

Figure 3. Box plots for selected SHPQ indicators before (T – 'traditional cultivation') and after subsoiling (S).

PAW and S index (calculated from the water retention curve) were not capable of distinguishing effects among treatments. In general, the highest S values were found in subsoiling soils suggesting that Dexter's S-index is improved by decrease bulk density and increase air capacity promoted by soil cultivation (Lozano et al., 2016).

In this study, the positive effect of soil subsoiling was observed in the case of increase of Ks values in both layers of 380% for topsoil and 94% for subsoil (Table 5 and 6; Fig. 3H). This emphasises the important role that subsoiling can play in mitigating water erosion loess soils (Kruk, 2017). On the basis of a study carried out by Wang et al., (2014) subsoiling enhance soil structure and improved infiltration. Liang et al., (2019) demonstrated that subsoiling can contribute to increasing the soil water retention. The study carried out by Wang et al., (2019) provided valuable information on soil sustainable use and management in loess soil.

Results of correlation analysis (for all layers before and after subsoiling) are reported in Tables 7 and 8. For soil before subsoiling significant correlations were observed between BD and S index with a negative relationship (r = -0.65, P < 0.05). Overall, soil variables shown interesting relationships. As concerns capacitive indicators derived from the soil water retention curve, a strong negative correlation was found between RFC and AC (r = -0.99, P < 0.05) as observed also in studies by Castellini et al., (2019). The PAW was strongly negatively related to AC (r = -0.58, P < 0.05) – a similar relationship has been observed by Zangiabadi et al., (2017), but strongly positively related to RFC (r = 0.62, P < 0.05). Moderate and strong correlation are observed between silt content and PAW, AC, RFC and Ks, with a positive and negative relationship respectively (r = 0.54, -0.51, 0.51 and -0.68 at P <0.05); in addition, clay content was positively correlated with S index (r = 0.52, P < 0.05). Neither static and dynamic indicators to evaluate SHPQ not correlated significantly with the saturated Ks; however, the silt and clay contents showed significant correlation with Ks, but only before subsoiling.

Table 7. Correlation matrix (Spearman Rho) for the soil before subsoiling.

Variables:	BD	PAW	AC	RFC	S	STI	TOC	Ks	sand	silt	clay
BD	1.00										
PAW	-0.16	1.00									
AC	-0.17	**-0.58**	1.00								
RFC	0.08	**0.62**	**-0.99**	1.00							
S	**-0.65**	0.05	**0.44**	**-0.35**	1.00						
StI	-0.22	-0.31	0.20	-0.14	0.18	1.00					
TOC	-0.23	-0.26	0.11	-0.05	0.17	**0.99**	1.00				
Ks	0.20	-0.12	0.03	-0.04	-0.17	-0.15	-0.18	1.00			
sand	0.25	-0.40	0.30	-0.31	-0.27	0.35	0.31	0.48	1.00		
silt	-0.29	**0.54**	**-0.51**	**0.51**	0.32	-0.41	-0.37	**-0.68**	**-0.87**	1.00	
clay	-0.49	0.49	-0.10	0.14	**0.52**	-0.32	-0.28	**-0.56**	**-0.82**	**0.74**	1.00

Note: **bold** type indicates significant correlations at P < 0.05

Table 8. Correlation matrix (Spearman Rho) for the soil after subsoiling.

Variables:	BD	PAW	AC	RFC	S	StI	TOC	Ks	sand	silt	clay
BD	1.00										
PAW	0.00	1.00									
AC	**-0.51**	**-0.73**	1.00								
RFC	**0.48**	**0.79**	**-0.96**	1.00							
S	**-0.79**	-0.05	**0.58**	**-0.51**	1.00						
StI	-0.16	-0.20	0.26	-0.18	0.02	1.00					
TOC	-0.18	-0.15	0.25	-0.15	0.07	**0.99**	1.00				
Ks	-0.21	0.03	0.07	-0.08	0.25	0.07	0.08	1.00			
sand	-0.03	-0.43	0.47	-0.40	0.16	0.37	0.37	-0.09	1.00		
silt	-0.06	0.49	-0.45	0.39	-0.01	-0.38	-0.40	0.14	**-0.95**	1.00	
clay	0.20	0.42	-0.49	0.43	-0.40	-0.36	-0.29	-0.30	**-0.77**	**0.60**	1.00

Note: **bold** type indicates significant correlations at P < 0.05

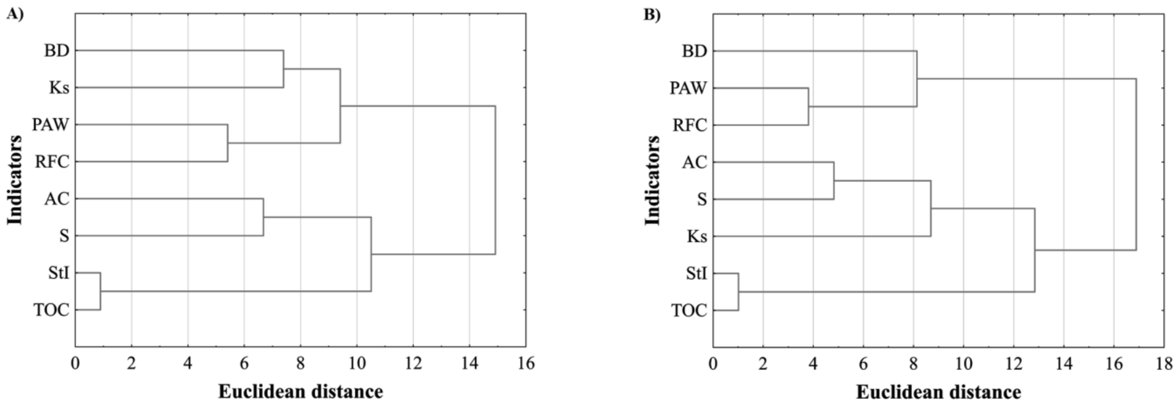

Figure 4. Dendrogram based on Ward's method considering evaluated soil hydro-physical indicators before (A) and after (B) subsoiling.

An interesting relationship was observed after subsoiling treatment. Loosening of the soil profile and reduce the compactness of the BD had affected significant on the three capacitive indicators (r = -0.51, 0.48 and -0.79, respectively for AC, RFC and S index) (Ghaemi et al., 2014). In addition, a negative correlation, although not significant (r = -0.21, P > 0.05), was found with Ks.

The levels of similarity are represented using a dendrogram based on cluster analysis and the Ward's method (Fig. 4). In this study observed two groups of indicators: similarity among BD, PAW and RFC as well as among AC, S index, StI and TOC. Also noted the highest dissimilarity of Ks regarding the other indicators. This indicator changes group after subsoiling (Fig. 4B). Zhang et al. (2019) reported that greater macroporosity (~AC) affects the hydraulic conductivity of saturated soil in the field (Ks). In both cases high similarity was found between StI and TOC. Both statistical correlations and cluster analysis presented results that corroborate each other.

4. CONCLUSIONS

The results of the research showed a positive and negative effects of subsoiling in a silty loam soils. Not all indicators show the very good or optimal levels of soil quality, it is therefore important that cumulative effects are comprehensively assessed with different soil properties. Compaction significantly deteriorated a silty loam soils physical quality, by, for example, decreasing AC, water retention expressed by the S index, and Ks. This study demonstrated that using subsoiling in a compacted silty loam soils leads to changes the most of their hydro-physical quality. These data show that subsoiling tillage can loosen the soil, fracture the plough pan, increase the availability and infiltration of soil moisture in subsoil layers. So, application of soil subsoiling, especially the loess soil, can improve physical and hydrological properties of silt-textured soils and reduce their compaction and increase water drainage by modification of Ks.

Some of soil hydro-physical properties are strongly associated with their particle size distribution and determined by soil pedogenesis. The effects of soil subsoiling are available in the literature, but now the climate change and sustainability of soil water management should be addressed. This highlights the need to consider the short-term changes in soil hydro-physical properties when modeling soil–crop systems.

Monitoring of soil hydro-physical quality in the agroecosystems is an important part of the diagnosis process of tillage systems in land-use, especially soil subsoiling because is laborious and expensive tillage system.

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REFERENCES

Abidela Hussein, M., Muche, H., Schmitter, P., Nakawuka, P., Tilahun, S.A., Langan, S., Barron, J. & Steenhuis, T.S., 2019. *Deep Tillage Improves Degraded Soils in the (Sub) Humid Ethiopian Highlands*. Land, 8, 159; https://doi.org/10.3390/land8110159

Abu-Hamdeh, N.H., 2003. *Compaction and subsoiling effects on corn growth and soil bulk density*. Soil Sci. Soc. Am. J., 67, 1213–1219. doi:10.2136/sssaj2003.1213

Arshad, M.A. & Martin, S., 2001. *Identifying critical* *limits for soil quality indicators in agroecosystems*. Agr. Ecosyst. Environ., 88, 153–160. https://doi.org/10.1016/S0167-8809(01)00252-3

Ateh, C., Bayles, M., Welbaum, G. & Mannes, J., 2016. *Soil: We Gotta Have It, But Will We?*. Published by Amer Society of Agronomy.

Bogdał, A., Kowalik, T., Borek, Ł. & Ostrowski, K., 2016. *Causes of excessive soil moisture in Prusy near Krakow*. Acta Sci.Pol. Form. Cir., 15, 3–19. http://dx.doi.org/10.15576/ASP.FC/2016.15.3.3

Borek, Ł., 2019. *The Use of Different Indicators to Evaluate Chernozems Fluvisols Physical Quality in the Odra River Valley: A Case Study*. Pol. J. Environ. Stud., 28, 4109–4116. DOI: https://doi.org/10.15244/pjoes/96259

Borek, Ł., Bogdał, A. & Ostrowski, K., 2018. *The Effect of Subsoiling on Changes of Compaction and Water Permeability of Silt Loam*. Rocz. Ochr. Sr. (Annual Set The Environment Protection), 20, 538––557. http://ros.edu.pl/

Botta, G.F., Jorajuria, D., Balbuena, R., Ressia, M., Ferrero, C., Rosatto, H. & Tourn, M., 2006. *Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields*. Soil Tillage Res., 91, 164–172. https://doi.org/10.1016/j.still.2005.12.011

Cameira, M.R., Fernando, R.M. & Pereira, L.S., 2003. *Soil macropore dynamics affected by tillage and irrigation for a silty loam alluvial soil in southern Portugal*. Soil Tillage Res., 70, 131–140. DOI: 10.1016/S0167-1987(02)00154-X

Castellini, M., Pirastru, M., Niedda, M. & Ventrella, D., 2013. *Comparing physical quality of tilled and no-tilled soils in an almond orchard in southern Italy*. Ital. J. Agron., 8, 149–157. https://doi.org/10.4081/ija.2013.e20

Castellini, M., Stellacci, A.M., Tomaiuolo, M. & Barca, E., 2019. *Spatial Variability of Soil Physical and Hydraulic Properties in a Durum Wheat Field: An Assessment by the BEST-Procedure*. Water, 11, 1434. https://doi.org/10.3390/w11071434

Catt, J.A., 2001. *The agricultural importance of loess*. Earth-Sci. Rev., 54, 213–229. https://doi.org/10.1016/S0012-8252(01)00049-6

Dexter, A.R., 2004a. *Soil physical quality; Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth*. Geoderma, 120, 201–214. https://doi.org/10.1016/j.geoderma.2003.09.004

Dexter, A.R., 2004b. *Soil physical quality: Part II. Friability, tillage, tilth and hard-setting*. Geoderma, 120, 215–225 https://doi.org/10.1016/j.geoderma.2003.09.005

Drewry, J.J., Cameron, K.C. & Buchan, G.D., 2008. *Pasture yield and soil physical property responses to soil compaction from treading and grazing: a review*. Aust. J. Soil Res., 46, 237–256.

Feng, X., Hao, Y., Latifmanesh, H., Lal, R., Cao, T., Guo, J., Deng, A., Song, Z. & Zhang, W., 2018. *Effects of Subsoiling Tillage on Soil Properties, Maize Root Distribution, and Grain Yield on Mollisols of Northeastern China*. Agron. J., 110, 1607-1615. doi:10.2134/agronj2018.01.0027

Ferreyra, R., Selles, G., Pinto, M., Morales, M. & Seguel, O., 2011. *Effect of soil air capacity on water relations and vegetative growth of 'Thompson seedless' grafted on different rootstocks: preliminary results*. Acta Hortic., 889, 145–150 ttps://doi.org/10.17660/ActaHortic.2011.889.15

Getahun, G.T., Kätterer, T., Munkholm, L.J., Parvage, M.M., Keller, T., Rychel, K. & Kirchmann, H., 2018. *Short-term effects of loosening and incorporation of straw slurry into the upper subsoil on soil physical properties and crop yield*. Soil Tillage Res., 184, 62–67. https://doi.org/10.1016/j.still.2018.06.007

Ghaemi, M., Astaraei, A.R., Emami, H., Nassiri Mahalati, M. & Sanaeinejad, S.H., 2014. *Determining soil indicators for soil sustainability assessment using principal component analysis of astan quds- east of mashhad- Iran*. J. Soil Sci. Plant Nutr., 14, 1005–1020. https://dx.doi.org/10.4067/S0718-95162014005000077

Hakl, J., Šantrůček, J., Kocourková, D. & Fuksa, P., 2007. *The effect of the soil compaction on the contents of alfalfa root reserve nutrients in relation to the stand density and the amount of root biomass*. Soil Water Res., 2, 54–58.

Hu, H., Tian, F. & Hu, H., 2011. *Soil particle size distribution and its relationship with soil water and salt under mulched drip irrigation in Xinjiang of China*. Sci. China Technol. Sci., 54, 1568. https://doi.org/10.1007/s11431-010-4276-x

Ishaq, M., Ibrahim, M., Hassan, A., Saeed, M. & Lal, R., 2001. *Subsoil compaction effects on crops in Punjab, Pakistan. II. Root growth and nutrient uptake of wheat and sorghum*. Soil Tillage Res., 59, 57–65. https://doi.org/10.1016/S0167-1987(00)00189-6

Islam, A., Mailapalli, D.R. & Behera, A., 2017. *Evaluation of Saturated Hydraulic Conductivity Methods for Different Land Uses*. Indian J. Ecol., 44, 456–466.

IUSS Working Group WRB. *World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps*. Rome: FAO, 2014, seria: World Soil Resources Reports No. 106. ISBN 978-92-5-108369-7.

Jin, K., Cornelis, W.M., Schiettecatte, W., Lu, J., Yao, Y., Wu, H., Gabriels, D., De Neve, S., Cai, D., Jin, J. & Hartmann, R., 2017. *Effects of different management practices on the soil-water balance and crop yield for improved dryland farming in the Chinese Loess Plateau*. Soil Tillage Res., 96, 131–144. https://doi.org/10.1016/j.still.2007.05.002

Kahlon, M.S. & Khurana, K., 2017. *Effect of land management practices on physical properties of soil and water productivity in wheat-maize system of northwest India*. Appl. Ecol. Env. Res., 15, 1–13. DOI: http://dx.doi.org/10.15666/aeer/1504_001013

Kanso, T., Tedolidi, D., Gromaire, M-Ch., Rameier, D., Saad, M. & Chebbo, G., 2018. *Horizontal and Vertical Variability of Soil Hydraulic Properties in Roadside Sustainable Drainage Systems (SuDS)—Nature and Implications for Hydrological Performance Evaluation*. Water, 10, 987; https://doi.org/10.3390/w10080987

Karlen, D.L., Mausbach, M. J., Doran, J.W., Cline, R.G., Harris, R.F. & Schuman, G.E., 1997. *Soil quality: A concept, definition, and framework for evaluation (A guest editorial)*. Soil Sci. Soc. Am. J., 61, 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x

Kondracki, J., 2011. *Regional Geography of Poland*. PWN, Warszawa. (In Polish)

Kruk, E., 2017. *Influence of daily precipitation on yield of eroded soil in mountain basin using the MUSLE model*. Acta Sci. Pol. Form. Cir., 16, 147–158. doi:10.15576/ASP.FC/2017.16.2.147.

Kundzewicz, W.Z., Førland, E.J. & Piniewski, M., 2017. *Challenges for developing national climate services –Poland and Norway*. Clim. Serv., 8, 17-25. https://doi.org/10.1016/j.cliser.2017.10.004

Liang, Y.F., Khan, S., Ren, A.-X., Lin, W., Anwar, S., Sun, M. & Gao, Z.-Q., 2019. *Subsoiling and sowing time influence soil water content, nitrogen translocation and yield of dryland winter wheat*. Agronomy, 9, 37. https://doi.org/10.3390/agronomy9010037

Liu, Z.D., Qin, A.Z., Ning, D.F., Zhao, B., Zhang, Z.D., Liu, Z.G., Nan, J.Q., Xiao, J.F. & Duan, A.W., 2016. *Subsoiling effects on grain yield and water use efficiency of spring maize in northern China*. Int. Agric. Eng. J., 25, 9–19.

Lozano, L.A., Soracco, C.G., Villarreal, R.R., Juan M., Sarli, G.O. & Filgueira, R.R., 2016. *Soil Physical Quality and Soybean Yield as Affected by Chiseling and Subsoiling of a No-Till Soil*. Rev. Bras. Ciênc. Solo., 40, e0150160. http://dx.doi.org/10.1590/18069657rbcs20150160

Ma, S., Yu, Z., Shi, Y., Gao, Z., Luo, L., Chu, P. & Guo Z., 2015. *Soil water use, grain yield and water use efficiency of winter wheat in a long-term study of tillage practices and supplemental irrigation on the North China Plain*. Agric. Water Manage., 150, 9-17. https://doi.org/10.1016/j.agwat.2014.11.011

Mari, G.R., Changying, J. & Jun, Z., 2008. *Effects of soil compaction on soil physical properties and nitrogen, phosphorus, potassium uptake in wheat plants*. Transactions of the Chinese Society of Agricultural Engineering. doi:10.3969/j.issn.1002-6819.2008.1.015

Moebius, B.N., van Es, H.M., Schindelbeck, R.R., Idowu, O.J., Clune, D.J. & Thies, J.E., 2007. *Evaluation of laboratory-measured soil physical properties as indicators of soil physical quality*. Soil Sci., 172, 895–912. DOI: 10.1097/ss.0b013e318154b520

Montgomery, D., Runger, G. & You, H., 2003. *Applied Statistics and Probability for Engineers, Student Workbook with Solutions*; John Wiley & Sons: New York, NY, USA.

Muršec, M., Leveque, J., Chaussod, R. & Curmi, P., 2018. *The impact of drip irrigation on soil quality in sloping orchards developed on marl – a case study*. Plant Soil Environ., 64, 20–25. DOI: 10.17221/623/2017-PSE

Nawaz, M.F., Bourrié, G. & Trolard, F., 2013. *Soil compaction impact and modelling. A review*. Agron. Sustainable Dev., 33, 291–309. https://doi.org/10.1007/s13593-011-0071-8

Olness, A., Clapp, C.E., Liu, R. & Palazzo, A.J., 1998. *Biosolids and their effects on soil properties. In Handbook of soil conditioners,* Wallace A, Terry RE (eds). Dekker M: New York, NY, 141–165.

Ostrowska, A., Gawliński, S., Szczubiałka, Z., 1991. *Methods for analyzing and assessing the properties of soil and plants*. Environmental Protection Institute, Warszawa. (in Polish)

Ottoni, M.V., Ottoni Filho, T.B., Lopes-Assad, M.L.R.C. & Rotunno Filho, O.C., 2019. *Pedotransfer functions for saturated hydraulic conductivity using a database with temperate and tropical climate soils*. J. Hydrol., 575, 1345-1358 https://doi.org/10.1016/j.jhydrol.2019.05.050

Pagliai, M., Vignozzi, N. & Pellegrini, S., 2004. *Soil structure and the effect of management practices*. Soil Tillage Res., 79, 131–143. doi:10.1016/j.still.2004.07.002

Paluszek, J., 2011. *Criteria of evaluation of physical quality of Polish arable soils*. Acta Agroph., 191, 1–139. (In Polish)

Paluszek, J., 2013. *Relationship of soil physical quality of Luvisols developed from moraine loams to their agricultural suitability*. Acta Agroph., 20, 651–663.

Peixoto, D.S., Silva, B.M., Godinho Silva, S.H., Karlen, D.L., Moreira, S.G., Pereira da Silva, A.A., Vilela de Resende, Á., Norton, L.D. & Curi, N., 2019. *Diagnosing, Ameliorating, and Monitoring Soil Compaction in No-Till Brazilian Soils*. Agrosyst. Geosci. Environ., 2, 180035. doi:10.2134/age2018.09.0035

Pieri, C.J.M.G., 1992. *Fertility of Soils: A Future for Farming in the West African Savannah*. Springer-Verlag. Berlin, Germany.

PN–R–04032. 1998. *Gleby i utwory mineralne. Pobieranie próbek i oznaczanie składu granulometrycznego*. PKN. (in Polish)

Polish Soil Classification. 2011. 5th Ed. Soil Science Annual. 62(3). (in Polish)

Reynolds, W.D., Bowman, B.T., Drury, C.F., Tan, C.S. & Lu, X., 2002. *Indicators of good soil physical quality: density and storage parameters*. Geoderma, 110, 131–146. https://doi.org/10.1016/S0016-7061(02)00228-8

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C.A. & Yang, X.M., 2009. *Use of indicators and pore volume-function characteristics to quantify soil physical quality*. Geoderma, 152, 252–263.

https://doi.org/10.1016/j.geoderma.2009.06.009

Reynolds, W.D., Drury, C.F., Yang, X.M. & Tan, C.S., 2008. *Optimal soil physical quality inferred through structural regression and parameter interactions*. Geoderma, 146, 466–474. https://doi.org/10.1016/j.geoderma.2008.06.017

Reynolds, W.D., Yang, X.M., Drury, C.F., Zhang, T.Q. & Tan, C.S., 2003. *Effects of selected conditioners and tillage on the physical quality of a clay of a clay loam soil*. Can. J. Soil Sci., 83, 381–393, https://doi.org/10.4141/S02-066

Schaller, N., 1993. *The concept of agricultural sustainability*. Agr. Ecosyst. Environ., 46, 89–97. https://doi.org/10.1016/0167-8809(93)90016-I

Schneider, F., Don, A., Hennings, I., Schmittmann, O. & Seidel, S.J., 2017. *The effect of deep tillage on crop yield–What do we really know?*. Soil Tillage Res., 174,193–204. DOI: 10.1016/j.still.2017.07.005

Schofield, R.K., 1935. *The pF of the water in soil*. Transactions of the 3rd International Congress of Soil Science, 2, 37–48.

Schoonover, J.E. & Crim, J.F., 2015. *An Introduction to Soil Concepts and the Role of Soils in Watershed Management*. J. Contemp. Water Res. Educ., 154, 21–47. doi:10.1111/j.1936-704X.2015.03186.x

Şeker, C. & Manirakiza, N., 2020. *Effectiveness of compost and biochar in improving water retention characteristics and aggregation of a sandy clay loam soil under wind erosion*. Carpathian Journal of Earth and Environmental Sciences, 15, 5–18. DOI:10.26471/cjees/2020/015/103

Shahab, H., Emami, H. & Karimi, A., 2013. *Pore size distribution as a soil physical quality index for agricultural and pasture soils in north-eastern Iran*. Pedosphere, 23, 312–320. https://doi.org/10.1016/S1002-0160(13)60021-1

Soil Survey Staff. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. 2nd Ed. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook, 1999.

Stefanidis, S. & Chatzichristaki, C., 2017. *Response of soil erosion in a mountainous catchment to temperature and precipitation trends*. Carpathian Journal of Earth and Environmental Sciences, 12, 35–39.

Sun, X., Ding, Z., Wang, X., Hou, H., Zhou, B., Yue, Y., Ma, W., Ge, J., Wang, Z. & Zhao, M., 2017. *Subsoiling practices change root distribution and increase post-anthesis dry matter accumulation and yield in summer maize*. Plos One, 12, e0174952.10.1371/journal.pone.0174952. https://doi.org/10.1371/journal.pone.0174952

Van Genuchten, M.TH., 1980. *A closed–form equation for predicting the hydraulic conductivity of unsaturated soils*. Soil Sci. Soc. Am. J., 44, 892–898.

Varsa, E.C., Chong, S.K., Abolaji, J.O., Farquhar, D.A. & Olsen, F.J., 1997. *Effect of deep tillage on soil physical characteristics and corn (Zea mays L.) root growth and production*. Soil Tillage Res., 43, 219–228. https://doi.org/10.1016/S0167-1987(97)00041-X

Velten, S., Leventon, J., Jager, N. & Newig, J., 2015. *What Is Sustainable Agriculture? A Systematic Review*. Sustainability, 7, 7833–7865. https://doi.org/10.3390/su7067833

Wang, H., Bai, W., Han, W., Song, J. & Lv, G., 2019. *Effect of subsoiling on soil properties and winter wheat grain yield*. Soil Use Manage., 35, 643– 652. https://doi.org/10.1111/sum.12524

Wang, Q., Lu, C., Li, H., He, J., Sarker, K.K., Rasaily, R.G., Liang, Z., Qiao, X., Li, H. & Mchugh, A.D.J., 2014. *The effects of no-tillage with subsoiling on soil properties and maize yield: 12-Year experiment on alkaline soils of Northeast China*. Soil Tillage Res., 137, 43-49. doi: 10.1016/j.still.2013.11.006

Wilding, L.P. & Drees, L.R., 1983. *Spatial variability and pedology*. In L. P. Wilding, N. E. Smeck, & G. F. Hall (Eds.), Pedogenesis and soil taxonomy: 1. Concepts and interactions (pp. 83– 116). Amsterdam: Elsevier.

Zangiabadi, M., Gorji, M., Shorafa, M., Khavari Khorasani, S. & Saadat, S., 2017. *Effects of Soil Pore Size Distribution on Plant Available Water and Least Limiting Water Range as Soil Physical Quality Indicators*. Pedosphere, 30, 253–262. https://doi.org/10.1016/S1002-0160(17)60473-9

Zhang, S.-Y., Hopkins, I., Guo, L. & Lin, H., 2019. *Dynamics of Infiltration Rate and Field-Saturated Soil Hydraulic Conductivity in a Wastewater-Irrigated Cropland*. Water, 11, 1632. https://doi.org/10.3390/w11081632

Ziernicka-Wojtaszek, A. & Krużel, J., 2016. *The Diversification of Air Temperature Trends in Poland (1981-2010)*. Pol. J. Environ. Stud., 25, 2205-2209. doi:10.15244/pjoes/62636.

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