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Analysis of the multi-annual effect of tillage systems and forecrops on texture and physical properties of soil

Analiza wieloletniego wpływu systemów uprawy i przedplonów na uziarnienie i właściwości fizyczne gleby

Abstract. The research topic was the analysis of the effect of multi-annual application of varied tillage systems and forecrops on soil texture and physical properties. The field experiments were carried out in Lipnik at the Agricultural Experimental Station belonging to the West Pomeranian University of Technology in Szczecin. Two factors were compared in the course of the experiment: factor one – three tillage systems: ploughing (A), ploughless (B), direct sowing (C); factor two – forecrop: one – faba bean, two – sugar beet. The tillage systems did not cause a change in the percentage share of silt and clay content in soil. The use of reduced tillage systems did not cause changes in field water capacity, in comparison with the conventional tillage system. With direct sowing, there was a significant increase in soil stability, as compared with ploughing (lower RDC values = 0.320 g (100 g)–1, RDC = susceptibility of soils to structure destruction, determined on the basis of the content of easily dispersible clay). This relationship was found only in the deeper layer of soil (0.05–0.20 m). The effect of reduced tillage was manifested in an increase of the value of S(f) indicator (indicator of soil susceptibility to physical degradation) and, consequently, structural degradation of soil. The use of faba bean as forecrop was also found to result in higher values of S(f).

Keywords: ploughing system, ploughless system, direct sowing, texture of soil, soil structure

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INTRODUCTION

Currently, for economic reasons, actions aimed at reducing agricultural production costs are promoted. One possible method of achieving this aim is the reduction of work involved in agrotechnical treatments. Reduced tillage consisting in reduced number of treatments is becoming increasingly popular [Dzienia et al. 2006, Majchrzak and Skrzypczak 2010] and correlates with the aforementioned method and aim. Three tillage systems are distinguished: ploughing (conventional), ploughless and zero tillage with direct sowing. The conventional tillage system i.e., ploughing, interferes with the soil structure to the greatest extent through inversion of topsoil. The ploughless and, particularly, direct sowing tillage disrupt soil constituents to a lesser extent. As a result of soil inversion, loosening, mixing, compaction and crumbling there is an initial change of physical properties of soil, particularly the water-air relationship, soil bulk density and compactness.

Numerous studies have shown that ploughing may lead to: soil compaction, erosion and of lower labor productivity rates [Murugan et al. 2013, Talarczyk et al. 2021]. Intensive ploughing leaves the soil exposed to rainfall and strong winds, therefore accelerating the erosion and degradation processes which, in turn, reduce the agronomic performance and quality of soil [Morris et al. 2010].

As topsoil is not displaced in ploughless tillage, the soil surface is protected against water and wind erosion, the crumby structure is protected against destruction, water evaporation is reduced, germination and emergence of weed is impeded, and soil microorganisms and earthworms are activated [Jaskulski and Jaskulska 2018].

Reduced tillage has a strong influence on the changes of strength parameters; there is an increase in soil compactness and maximum shear stress [Białczyk et al. 2007]. The results of a three-year long study by Pabin et al. [2007] show that application of diversified tillage systems caused permanent changes in the physical condition of soil and, with zero tillage, resulted in an increase in soil density to a certain stable level, as compared with the conventional tillage. Other authors, Aikins and Afuakwa [2012], discussing the effects on soil physical properties of four different tillage treatments consisting of: disc plowing followed by harrowing, disc plowing, harrowing only and no tillage, found that tillage treatments significantly affected, penetration resistance, dry bulk density, moisture content and porosity.

The aforementioned findings can be concluded, following Jaskulski et al. [2015], that shallow no-till treatment applied instead of ploughing, regardless of the forecrops, resulted in an increased compaction, bulk density, soil moisture and soil mineral nitrogen content after subsequent crops harvest.

The aim of this research was to verify the following hypotheses:

– tillage systems change the texture and physical properties of soil,

– forecrops change the texture and physical properties of soil.

The experience was carried out over a period of 25 years. The aim of the research based on the results of many years of field experiments was to compare the effects obtained during tillage in three cultivation systems: ploughing system, ploughless system, direct sowing after forecrops of faba beans and sugar beet. By comparing three tillage systems and two forecrops, changes in texture and physical properties of soil were analyzed.

MATERIAL AND METHODS

Study area

The field experiments were carried out in Lipnik (53°41'N, 14°97'E) at the Agricultural Experimental Station belonging to the West Pomeranian University of Technology in Szczecin. The experiment was carried out over the period of 25 years – it was established in 1994 and the last soil samples were taken in 2019. The soil belongs to arable soil, medium quality, worse. The soil originated from loamy sand (LS) [PTGleb 2009]. The soil was classified as Rusty brown soil [Kabała et al. 2019]. The thickness of humus layer is 14–25 cm, humus content is 1.3–1.5% and the content of alluvial elements is 11–13%. This is a light soil characteristic for the region of West Pomerania. The field experiment was conducted with the use of winter wheat in a three-field crop rotation system (sugar beet – winter wheat – faba bean). The plants were cultivated on plots of an area of 40 m^2 (to harvest 30 m^2).

Winter wheat of "Kobra Plus" cultivar was grown in three tillage systems: ploughing (A), ploughless using a cultivator and string roller (B) and direct sowing (C). For the conventional (A) and ploughless tillage (B), winter wheat was sown using a row drill seeder. As for objects with direct sowing, a special seeder (for direct sowing) was used. The cultivar used in the experiment, i.e., 'Kobra Plus', is a bread cultivar of cold hardiness estimated as 4° (in the scale of 9°).

Two factors were compared in the course of the experiment: factor one – three tillage systems: ploughing (A), ploughless (B), direct sowing (C); factor two – forecrop: one – sugar beet ('Kutnowska' cultivar), two – faba bean ('Martin' cultivar).

Soil analyses

Soil samples were collected using Egner's soil samples from two depths: 0.0–0.05 and 0.05–0.20 m. Single soil samples (n = 10) were collected from each replication from individual plots and collective samples were created from them. Collective samples were took in the analyses, number of replications was three. The samples were taken after the harvest of the plants. The samples were dried and ground according to the requirements set out in the norm the Polish Standard [ISO 10381–2:2007]. Texture was determined with aerometric method by Casagrande, modified by Prószyński [DIN-R-04032:1998].

Total content of carbon (C), was determined with the use of elemental analyser CHNS (Costech Instruments Elemental Combustion System) by ELTRA Poland. The organic matter (OM) content was calculated using the formula OM = Ctot.*1.724.

Using the content of organic matter and percentage share of soil particle distribution, the values of soil physical properties parameters were calculated for both layers of soils. Field water capacity (FWC), moisture of initial plant growth inhibition start (MIPGIS) and moisture of permanent wilting point (MPWP) were calculated using the following equations by Trzecki [1974]:

$$FWC = 0.0188x_1 + 0.0879x_2 + 0.240x_3 + 0.296x_4 + 0.649x_5 + 0.316x_6 + 2.34x_7,$$

$$MIPGIS = -0.0213x_1 - 0.0338x_2 + 0.115x_3 + 0.451x_4 + 0.513x_5 + 0.323x_6 + 2.25x_7,$$

$$MPWP = 0.00121x_1 - 0.00868x_2 + 0.0488x_3 + 0.0737x_4 + 0.0485x_5 + 0.142x_6 + 1.25x_7.$$

where: x_1 – % by weight of the fraction 1.0–0.1 mm; x_2 – 0.1–0.05 mm; x_3 – 0.05–0.02 mm; x_4 – 0.02–0.006 mm; x_5 – 0.006–0.002 mm; x_6 < 0.002 mm; x_7 – % organic matter.

For the assessment of soil susceptibility to physical degradation, the indicator by Pieri [1989] was used. The indicator – S(f) – is based on the concept that the level of physical degradation of soil (decreased durability of soil aggregates, bulk density, porosity, water permeability etc.) relates to the ratio of organic matter content (OM) to the sum of silt and clay. S(f) = [OM (%) × 100] / [clay (%) + silt (%)]. The assessment of the level of soil susceptibility to physical degradation, developed by Schroth [2003], is as follows: the value S(f) < 5 describes degraded structures highly susceptible to erosion; 5 < S(f) < 7 structures at high risk of structural degradation; 7 RDC< S(f) < 9 soils at low risk of structural degradation; indicator > 9 shows soils with insufficient amount of organic matter to ensure the durability of a stable structure.

Readily dispersible clay content (RDC) was determined turbidimetrically on grounds of soil colloids dispersion. This method was developed through adaptation to conditions adequate to sandy soil in Poland [Czyż et al. 2002, Dexter and Czyż 2011]. The grounds were provided by the description of the method by Kay and Dexter [1992] and Watts et al. [1996].

For the tested soils, the class of susceptibility to structure destruction was determined according to Czyż [2003] based on the content of easily dispersible clay [g $(100\ g)^{-1}$ soil], calculated based on the formula:

RDC = exp(–1.40 + 0.508·log(% colloidal clay) – 0.735·log(OM)), where:

– exp – inverse function of the natural logarithm of a number;

– % colloidal clay – content of the soil particles with a diameter below 0.002 mm according to PTG (1989),

– OM – humus content (%).

On the basis of the determination of readily dispersible clay content [RDC g $(100\ g)^{-1}$ soil], five classes of soil susceptibility to destruction were distinguished [Czyż 2003]:

I – very highly susceptible soils >0.50;

II – highly susceptible soils 0.41–0.50;

III – susceptible soils 0.31–0.40;

IV – weakly susceptible soils;

V – very weakly susceptible soils ≤0.20.

Statistical analysis

The results of two factor experiment were statistically processed using the analysis of variance in complete randomization design. Confidence sub-intervals were calculated using Tukey's multiple test, assuming a significance level at $P < 0.05$ [Hill and Lewicki 2006]. The statistical analysis of the obtained results was carried out using the Statistica 10.0 software.

RESULTS

Soil texture

Significance of the main effects and interactions between the factors under study, determined with the analysis of variance (ANOVA), is presented in Table 1. The tillage systems did not cause a change in the percentage share of silt and clay content in soil.

Table 1. Significance of variability sources from ANOVA and coefficient of variance (V%) for estimated soil properties

Property	Layer (m)	Source of variability			V%
		forecrop (F)	tillage system (C)	interaction (F × C)	
Skeleton ϕ > 2 mm	0–0.05	ns	ns	ns	19.20
	0.05–0.20	ns	ns	ns	21.60
Sand ϕ = 2–0.05 mm	0–0.05	ns	ns	ns	2.23
	0.05–0.20	ns	ns	ns	2.86
Silt ϕ = 0.05–0.002 mm	0–0.05	*	ns	ns	13.03
	0.05–0.20	**	ns	ns	9.87
Clay ϕ < 0.002 mm	0–0.05	ns	ns	ns	17.06
	0.05–0.20	**	ns	ns	18.60
Field water capacity	0–0.05	ns	ns	ns	7.65
	0.05–0.20	**	ns	ns	6.11
Moisture of initial plant growth inhibition start	0–0.05	*	ns	*	4.67
	0.05–0.20	ns	ns	ns	11.67
Moisture of permanent wilting of plants	0–0.05	***	**	ns	6.11
	0.05–0.20	ns	ns	ns	10.12
Indicator of soil susceptibility to physical degradation	0–0.05	***	**	ns	2.67
	0.05–0.20	***	**	ns	6.27
Readily dispersible clay content	0–0.05	ns	ns	ns	6,47
	0.05–0.20	ns	*	ns	7.52

V% – coefficient of variance
* significance at 0.05; ** significance at 0.01; *** significance at 0.001; ns – no significance

Texture, defined as the fragmentation of the mineral part of the solid phase, is a basic physical property which affects all physical properties of soil. In both layers of soil, there was no significant effect of forecrop and tillage system on the changes of percentage share of the skeleton and sand in the texture of soil in the experiment. The tillage systems under analysis – ploughing (A), ploughless (B) and direct sowing (C), did not result in changes of the percentage share of silt and clay in soil (Tabs 1 and 2). The silt is mainly quartz, whereas the clay is predominantly composed of secondary aluminosilicates – clay minerals created as a result of weathering of primary aluminosilicates [Brady and Weil 1999]. The results obtained in the experiment showed the effect of forecrop on the percentage share of silt in soil in both layers, and clay in the layer 0.05–0.20 m (Tab. 1). Cultivation of sugar beet resulted in the significantly higher content of silt – 16.9%, as compared with faba bean. The percentage share of clay was the significantly higher in soil where faba bean was grown as forecrop (Tab. 2).

Table 2. Soil particle content (%)

Property	Factor	Variant	Layer	
			0–0.05 m	0.05–0.20 m
Skeleton ϕ > 2 mm	forecrop	faba bean	3.7^{a} ±0.47	3.0^{a} ±0.33
		sugar-beet	3.0^{a} ±0.34	2.7^{a} ±0.24
	tillage system	A	3.6^{a} ±0.42	2.8^{a} ±0.34
		B	3.8^{a} ±0.71	2.9^{a} ±0.32
		C	2.8^{a} ±0.30	2.8^{a} ±0.43
Sand ϕ = 2–0.05 mm	forecrop	faba bean	79.8^{a} ±0.32	80.4^{a} ±0.87
		sugar-beet	78.7^{a} ±0.22	78.7^{a} ±0.18
	tillage system	A	79.1^{a} ±0.42	79.6^{a} ±0.58
		B	78.4^{a} ±0.22	78.9^{a} ±0.54
		C	80.3^{a} ±0.39	80.1^{a} ±1.18
Silt ϕ = 0.05-0.002 mm	forecrop	faba bean	14.5^{b} ±0.76	14.5^{b} ±0.51
		sugar-beet	16.9^{a} ±0.35	16.9^{a} ±0.31
	tillage system	A	16.1^{a} ±0.80	15.3^{a} ±0.72
		B	16.5^{a} ±0.63	15.9^{a} ±0.56
		C	14.4^{a} ±0.88	15.0^{a} ±0.79
Clay ϕ < 0.002 mm	forecrop	faba bean	5.7^{a} ±0.40	5.1^{a} ±0.53
		sugar-beet	4.4^{a} ±0.33	4.4^{b} ±0.25
	tillage system	A	4.8^{a} ±0.50	5.1^{a} ±0.38
		B	5.1^{a} ±0.61	5.2^{a} ±0.40
		C	5.3^{a} ±0.37	4.9^{a} ±0.67

The same letters indicate no significant differences
Tillage systems: (A) ploughing, (B) ploughless using a cultivator and string roller, (C) direct sowing

Physical properties of soil

Soil water properties are predominantly determined by three properties: field water capacity (FWC), moisture of initial plant growth inhibition start (MIPGIS) and moisture of permanent wilting of plants (MPWP).

Field water capacity (FWC) is a parameter of water-soil characteristics representing water content determined in soil after free outflow of gravitational water from a particular layer of soil which was previously completely filled with water, in the absence of the impact of groundwater and interruption of soil oxygen evaporation. Under such conditions, the water which remains in soil can be retained by capillary forces. It is dependent on soil water binding potential. The changes in the values depend on the soil texture, its structure, density and humus content [Łopatka et al. 2007].

The field water capacity of the soil in the experiment, expressed as a weight percentage, was between 10.2 and 11.0%. But only in the case of sugar beets grown as a forecrop there was an increase in field water capacity up to 11% in the soil at a depth of 0.05–0.20 meters. There was no significant effect of the applied tillage systems on the changes of field water capacity (Tabs 1 and 3).

Table 3. Physical properties of soil

Property	Factor	Variant	Layer	
			0–0.05 m	0.05–0.20 m
Field water capacity (%)	forecrop	sugar-beet	$10.8^{a} \pm 0.16$	$11.0^{a} \pm 0.18$
		faba bean	$10.5^{a} \pm 0.23$	$10.2^{b} \pm 0.20$
	tillage system	A	$10.6^{a} \pm 0.35$	$10.2^{a} \pm 0.20$
		B	$10.7^{a} \pm 0.25$	$10.8^{a} \pm 0.18$
		C	$10.6^{a} \pm 0.19$	$10.9^{a} \pm 0.36$
Moisture of initial plant growth inhibition start (%)	forecrop	sugar-beet	$6.48^{b} \pm 0.054$	$6.70^{a} \pm 0.136$
		faba bean	$6.75^{a} \pm 0.147$	$6.13^{a} \pm 0.303$
	tillage system	A	$6.43^{a} \pm 0.123$	$6.12^{a} \pm 0.123$
		B	$6.81^{a} \pm 0.179$	$6.82^{a} \pm 0.123$
		C	$6.61^{a} \pm 0.088$	$6.82^{a} \pm 0.144$
Moisture of permanent wilting of plants (%)	forecrop	sugar-beet	$2.77^{b} \pm 0.053$	$2.74^{a} \pm 0.047$
		faba bean	$3.07^{a} \pm 0.074$	$2.84^{a} \pm 0.104$
	tillage system	A	$2.73^{b} \pm 0.059$	$2.79^{a} \pm 0.058$
		B	$2.99^{a} \pm 0.111$	$2.91^{a} \pm 0.076$
		C	$3.04^{a} \pm 0.076$	$2.76^{a} \pm 0.139$
Indicator of susceptibility of soil humus layer to physical degradation	forecrop	sugar-beet	$5.44^{b} \pm 0.088$	$5.40^{b} \pm 0.113$
		faba bean	$5.95^{a} \pm 0.125$	$5.99^{a} \pm 0.125$
	tillage system	A	$5.39^{b} \pm 0.098$	$5.41^{b} \pm 0.159$
		B	$5.70^{ab} \pm 0.152$	$5.68^{ab} \pm 0.142$
		C	$6.00^{a} \pm 0.155$	$6.00^{a} \pm 0.182$
Readily dispersible clay content [g (100 g)$^{-1}$]	forecrop	sugar-beet	$0.342^{b} \pm 0.0039$	$0.342^{a} \pm 0.0057$
		faba bean	$0.341^{a} \pm 0.0075$	$0.340^{a} \pm 0.0104$
	tillage system	A	$0.350^{a} \pm 0.0083$	$0.358^{a} \pm 0.0038$
		B	$0.341^{a} \pm 0.0074$	$0.345^{ab} \pm 0.0046$
		C	$0.333^{a} \pm 0.0052$	$0.320^{b} \pm 0.0139$

The same letters indicate no significant differences
Tillage systems: (A) ploughing, (B) ploughless using a cultivator and string roller, (C) direct sowing

Water contained in the soil is only partly available to plants, and its availability depends on water binding force, i.e. soil suction force, which is a sum of osmotic, hydrostatic, gravitational, molecular and capillary forces. It is generally accepted that the optimum moisture conditions for the growth and development of plants occur at soil moisture content of 60–80% of field water capacity (FWC). Then the amount of soil air (oxygen) does not limit the growth and functioning of the root system, and the water is readily available to plants [Kuś 2016]. The soil in the experiment was characterised by moisture of initial plant growth inhibition start in the range of 6.12–6.82%, which was above 60% of field water capacity. The use of reduced tillage systems did not cause changes in soil moisture, in comparison with the conventional tillage system. Only in the case of sugar beet grown as forecrop, there was a significant decrease in moisture of initial plant growth inhibition start in topsoil to 6.48%, and a particularly marked effect of forecrop was identified in the case of ploughless tillage system (Tabs 1 and 3).

Another concept describing soil moisture is the moisture of permanent wilting of plants (MPWP), which represents soil moisture at which water is retained in soil with forces exceeding the root suction force, resulting in unavailability of water to plants and their permanent wilting [Kuś 2016]. Moisture of permanent wilting of plants in the soil used in the experiment was from 2.73 to 3.07%. The effect of the tillage system was identified in topsoil (0–0.05 m). With ploughing, the values of moisture of permanent wilting of plants were found to be the lowest, 2.73%. The identified relationships can be explained by the fact that with the conventional tillage system i.e., ploughing, the interference with the soil structure is the greatest. Similarly as in the case of moisture of initial plant growth inhibition start, the use of sugar beet as forecrop was found to result in a significant decrease of moisture of permanent wilting of plants in topsoil to 2.77 (Tabs 1 and 3).

The basic parameters used for calculating the indicator of soil susceptibility to physical degradation – S(f) are the content of organic matter and the sum of silt and clay [Radziuk and Świtoniak 2021]. On the basis of the S(f) indicator, the soil is to be characterised as highly susceptible to structural degradation (Tab. 3), [Schroth 2003]. Both factors under analysis i.e., tillage system and forecrop, resulted in change of S(f) indicator (Tab. 1). The effect of reduced tillage systems was manifested in an increase of S(f) indicator, therefore indicating structural soil degradation. With direct sowing (C), in soil from two layers, the identified S(f) indicator was the highest (6.00). Faba bean used as forecrop resulted in higher values of S(f) which amounted to 5.95 and 5.99 in the layers, respectively (Tab. 3).

The key component of soil is clay [Czyż 2005]. Generally, high content of readily dispersible clay (RDC) in soil means that clay is loosely bound in soil aggregates and soil is susceptible to dispersion and cementation during wetting and drying [Czyż and Vizitiu 2012].

On the basis of the values of readily dispersible clay (RDC), the soil from the experiment is to be characterised as susceptible to destruction [Czyż 2003]. With direct sowing, there was a significant increase in soil stability, as compared with ploughing [lower RDC values = 0.320 g $(100\ g)^{-1}$]. This relationship was found only in the deeper layer of soil (0.05–0.20 m) – Table 3.

Interaction between the factors (forecrop, tillage system) was identified sporadically, only in one case. The accuracy of the experiment with respect to the traits under analysis is to be considered satisfactory – in most cases the coefficient of variation (V%) amounted to 10% which indicates high accuracy of the experiment.

DISCUSSION

Stability of soil aggregates is a basic property of soil affecting its balance and crop production, and is connected with texture [Amézketa 1999]. The results obtained in the experiment showed the effect of forecrop on the percentage share of silt in soil in both layers, and clay in topsoil. The multi-annual effect of a particular tillage system affects the physical properties of soil in a permanent manner appropriate for a given system [Jaskulski et al. 2015].

However, according to the results of the experiment with the use of corn and wheat by Liu et al. [2021], in comparison with the conventional tillage, reduced tillage resulted in an increase of water retention in soil.

In the current study, with direct sowing, there was a significant increase in soil stability, as compared with ploughing. This relationship was found only in the deeper layer of soil. Czyż and Dexter [2009], in their study on the effects of reduced tillage on physical properties of lessive soil, found that the application of reduced tillage resulted in a twofold decrease in the readily dispersible clay content (RDC) in soil, thus causing an improvement in soil stability. According to Drzymała and Mackiewicz [2004], the continued application of direct sowing for the period of 5 years contributed to a pronounced change in the structure of topsoil which was conclusively confirmed both with field as well as laboratory methods. The effect was most prominent in the increase in soil aggregate diameter and, particularly, in the increase of aggregate resistance to static and dynamic action of water. The studies by Dexter et al. [2008] show that complex organic carbon in soil determined numerous physical properties of soil, among others: stability of soil structures and physical quality of soil. This is because clay in soil can create complexes with organic matter (SOM), does not undergo dispersion readily consequently making the soil more stable. Also, the authors demonstrated that non-complexed clay undergoes dispersion on contact with water more readily.

CONCLUSION

In both layers of soil, there was no significant effect of forecrop or tillage system on changes in the percentage share of the skeleton and sand in texture of soil from the experiment. The tillage systems under analysis i.e., ploughing, ploughless and direct sowing did not cause a change in the percentage share of silt and clay content in soil. There was no significant effect of the applied tillage systems on the changes of field water capacity and soil moisture, in comparison with the conventional tillage. Sugar beet used as forecrop was identified as the factor causing a significant decrease, in topsoil, of the moisture of initial plant growth inhibition. Particularly pronounced effect was identified with ploughless tillage system. With ploughing, the values of moisture of permanent wilting of plants were found to be the lowest. Similarly as in the case of moisture of initial plant growth inhibition start, sugar beet grown as forecrop caused a significant decrease of moisture of permanent wilting of plants in topsoil. The effect of reduced tillage was manifested in an increase of the value of S(f) indicator and, consequently, structural degradation of soil. With direct sowing, in the two layers of soil, the values of S(f) were the highest and amounted to 6.00. The use of faba bean as forecrop was found to result in higher values of S(f). Direct sowing caused a significant increase in soil stability in comparison with ploughing. However, this relationship was identified only with respect to the deeper layer of soil.

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