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Physical properties of soil after 54 years of long-term fertilization and crop rotation

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ABSTRACT

The investigations were carried out in two permanent fertilization experiments established in 1955 on the black earth in Chylice, near Warsaw, Mazovian province, Poland. The aim of this study was to compare the impact of long-term mineral (NPK); organic (FM) and mixed mineral-organic (½ NPK + ½ FM) fertilization in two crop rotations on some soil physical properties, including the soil structure, dry bulk density, soil moisture and field water capacity. The fertilization systems and using red clover in crop rotation significantly influenced soil structure and water conditions. Farmyard manure (FM, ½ NPK + ½ FM) application in both crop rotations increased mean weight diameter of water-resistant aggregate, water aggregate stability and field water capacity in comparison to unfertilized and mineral treatments. The dry soil bulk density was lower in soil fertilized with farmyard manure than in soil unfertilized. The most favourable effect on physical soil properties exerted farmyard manure (FM, ½ NPK + ½ FM) in crop rotation with red clover. A positive correlation was also proved between the soil structure parameters and field water capacity.

Keywords: nutrients; soil fertility and quality; arable layer; water resistance

Plant production is dependent on the soil fertility and the availability of nutrients air and water for plants (Xue et al. 2003).

Plants need large quantities of water for growth. It is known that field water capacity and the amount of water available for plants are connected with the parent material, especially with the granulometric composition of soils, but also with the soil structure and the organic carbon content (Walczak et al. 2002).

The organic carbon content is one of the main soil characteristics, which determines soil fertility (Celik 2005, Liu et al. 2005). The soil structure, especially water resistance of soil aggregate, is one of the most important factors affecting relative capacities to retain water in soil (Oades 1984, Abrishamkesh et al. 2011). Formation and stability of soil structure is influenced by many agronomic factors, especially methods of soil tillage, fertilization systems and crop rotation (Franzluebbers 2002, Suwara and Szulc 2011).

Crop rotation with perennial plants and regular supplies of organic fertilizers have the positive influence on soil productivity, raise the soil quality for crop production by increasing the soil organic matter and improving soil structure (Schjønning et al. 2002, Tejada et al. 2009, Talgre et al. 2012, Słowińska-Jurkiewicz et al. 2013). Different fertilization and crop rotation can affect the soil aggregate stability and water availability. Farmyard manure is considered as one of the most effective fertilizers in creating of soil fertility. Red clover as a deep-rooted crop creates channels, increases soil organic matter, improves soil structure and reduces soil compaction. It is one of the most common and important plants which leads to decline of the use of synthetic nitrogen fertilizers and herbicides (Gaudin et al. 2013).

Long-term field experiments are essential for assessment of fertilization and crop rotation effects on soil fertility. They provide the best possible means to observe changes in soil properties

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(Seremesic et al. 2011, Suwara and Szulc 2011, Verma et al. 2012, Neugschwandtner et al. 2014).

The aim of this study was to assess the long-term effects of fertilization (mineral, organic and mixed mineral-organic) in two crop rotations (Norfolk rotation and crop rotation without legumes) on some physical properties of black earth.

MATERIAL AND METHODS

Long-term fertilization experiments were established on the black earth classified as Endogleyic Phaeozem according to the World Reference Base for Soil Resources (WRB) with the granulometric composition of sandy loam in Chylice near Warsaw (52°06'N, 20°33'E), Poland in 1955 by the Department of Agronomy, Warsaw University of Life Science.

The prevailing climate of this region is temperate, with annual precipitation of 580 mm and mean annual temperature of 7.5°C. The arable layer (0–20 cm) had the following properties: pH_{KCl} 6–6.5, organic carbon 8–11 g/kg in crop rotation without legumes and 12–15 g/kg in Norfolk rotation.

In the two experiments four fertilizer treatments were compared: mineral fertilization (NPK); farmyard manure (FM); mixed mineral and organic fertilization (½ NPK + ½ FM) and control without any fertilization (O). These four treatments with four replications were designed in randomized blocks. Fertilizers were applied in two crop rotations:

(A) Norfolk rotation: sugar beet-spring barley with undersown red clover-red clover-winter wheat (each crop grown every 4 years);

(B) without legumes crops: sugar beet-spring barley-winter rape-winter wheat (each crop grown every 4 years).

Soil samples for analyses of soil physical properties were taken from the arable layer (0–20 cm) in June 2009 during vegetation of winter wheat after 54 years of experiments conducting.

To determine soil structure, the soil samples were collected from five places of each plot, joined into one sample (3 kg) and carefully mixed by hand. Then they were air-dried and sifted by 10 mm mesh sieve to remove soil particles above 10 mm.

Next the fraction below 10 mm (0.5 kg) has been sifted for 2 min on a set of sieves 7; 5; 3; 1; 0.5 and 0.25 mm meshes. The aggregates remaining on each sieve were weighed and then the percentage of each fraction was calculated. The mean weight diameter of dry aggregates (MWDa) was calculated (Rewut 1980).

$$MWDa = \frac{\sum i = lxiwi}{m} \quad (1)$$

Where: i – subsequent aggregate fraction; x – the mean diameter of successive aggregate fraction; w – mass of dry resistant aggregates left on i^{th} sieve of a set of sieves; m – mass of the soil sample.

To obtain a representative soil sample for water resistance of soil aggregates analysis, after dry sifting, 10% from each fraction of aggregates was taken, joined and gave an average 50 g soil sample. In the wet sifting a separator for soil aggregates was used with a set of sieves with 7; 5; 3; 1; 0.5 and 0.25 mm meshes, constructed in the Institute of Agrophysics of the Polish Academy of Sciences, Lublin.

The analysis was conducted for 12 min. Then the aggregates from each sieve were air-dried, weighed and the results were calculated in percents in relation to the initial sample weight.

The stability of the granular structure was expressed by the mean weight diameter of water-resistant aggregates (MWDw) and index of water resistance (Ww):

$$MWDw = \frac{\sum i = lxiwi}{m} \quad (2)$$

Where: i – subsequent aggregate fraction; x – the mean diameter of successive aggregate fraction; w – mass of wet resistant aggregates left on i^{th} sieve of a set of sieves, m – mass of the soil dry aggregates.

$$Ww = \frac{MWDw}{MWDa} \times 100\ (\%) \quad (3)$$

Core samples of depth 5–10 cm were taken from the same location by a steel core sampler of a 100 cm^3 volume, with four replications, for dry bulk density and field water capacity. The dry bulk density was determined by the core method. The water content of soil samples at field capacity was determined using the pressure plate apparatus of Soil Moisture Equipment (Santa Barbara, USA) at –0.01 MPa and –0.025 MPa (Dane and Topp 2002). Gravimetric water content of the soil was measured in the laboratory by weighting the soil samples after collecting them from the field and after drying at 105°C in an oven for 48 h in four replications.

Analysis of variance was performed using Statgraphics 4.1 software (Rockville, USA) to determine the significance of fertilization system and

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Table 1. Effects of fertilization on wet mean weight diameter (MWDw) and water stability of aggregates (Ww)

Treatment	MWDw (mm)			Ww (%)		
	A	B	mean	A	B	mean
Unfertilized	0.75	0.59	0.67	26.2	23.3	24.7
NPK	0.80	0.66	0.73	28.6	24.7	26.6
Farmyard manure	0.97	0.73	0.85	34.6	27.8	31.2
½ NPK + ½ FM	0.84	0.72	0.78	29.9	27.5	28.7
Mean	0.84	0.68		29.8	25.8	
$LSD_{0.05}$	fertilization (I) 0.08 crop rotation (II) 0.11 interaction (I × II) 0.20			fertilization (I) 2.1 crop rotation (II) 2.3 interaction (I × II) 3.3		

A – Norfolk rotation; B – crop rotation without red clover

crop rotation on soil properties. The Tukey's test was used to separate means of the measured values.

Relationships between dry bulk density, soil structure indexes and field water capacity were calculated using correlation analysis and linear regression. For all analyses, significance level was set at 0.05.

RESULTS AND DISCUSSION

From these studies, it can be found that changes occur in physical soil properties, which are caused by the influence of cultivated plants in crop rotations and fertilization systems.

The dry MWDa of soil aggregates did not differ between the four fertilization systems in both crop rotations and ranged from 2.80–2.86 mm in treatments with Norfolk rotation and from 2.54–2.73 mm in crop rotation without red clover.

The fertilization and crop rotation systems differentiated not only the water-resistant aggregate composition of soil but also the mean weight diameter of wet aggregate and index of soil water resistance (Table 1).

The wet MWDw of aggregates in both experiments was significantly greater in the treatments with farmyard manure compared to mineral and unfertilized plots. The water resistance showed differences between the compared treatments in both experiments. The highest water resistance of aggregates was recorded in the soil with farmyard manure application (FM, ½ NPK + ½ FM). The smallest stability of aggregates was observed in unfertilized soil or with application only mineral fertilizers. Additionally using red clover in crop rotation since 1955 favourably influenced soil structure and aggregate stability.

An increase in soil organic matter with addition of farmyard manure and cultivation of red clover led

Table 2. Effects of fertilization and crop rotation on soil dry bulk density at 5–10 cm depth (t/m^3)

Fertilization	Crop rotation		Mean
	Norfolk	without red clover	
Unfertilized	1.60	1.69	1.65
NPK	1.58	1.66	1.62
Farmyard manure	1.57	1.60	1.59
½ NPK + ½ FM	1.61	1.60	1.61
Mean	1.59	1.64	
$LSD_{0.05}$	fertilization (I) – ns crop rotation (II) – 0.04 interaction (I × II) – 0.08		

ns – not significant

Table 3. Effects of fertilization and crop rotation on soil water content (% w/w)

Fertilization	Crop rotation		Mean
	Norfolk	without red clover	
Unfertilized	14.5	11.5	13.0
NPK	13.9	13.1	13.5
Farmyard manure	16.1	15.5	15.8
½ NPK + ½ FM	15.3	15.0	15.2
Mean	14.9	13.8	
$LSD_{0.05}$	fertilization (I) – 1.41 crop rotation (II) – 1.00 interaction (I × II) – 2.00		

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Table 4. Effects of fertilization and crop rotations on field water capacity of –0.01 MPa (pF 2) and –0.025 MPa (pF 2.4) (% w/w)

Fertilization	–0.01 MPa			–0.025 MPa		
	A	B	mean	A	B	mean
Unfertilized	15.9	13.1	14.5	14.7	12.1	13.4
NPK	15.8	14.5	15.2	14.8	13.4	14.1
Farmyard manure	17.5	16.9	17.2	16.4	15.8	16.1
½ NPK + ½ FM	16.7	16.3	16.5	15.6	15.3	15.5
Mean	16.5	15.2		15.4	14.2	
$LSD_{0.05}$	fertilization (I) – 1.70 crop rotation (II) – ns interaction (I × II) – 2.40			fertilization (I) – 1.71 crop rotation (II) – ns interaction (I × II) – 2.42		

A – Norfolk rotation; B – crop rotation without red clover; ns – not significant

to formation of water stability aggregates (Oades 1984, Gaudin et al. 2013, Wang et al. 2013).

To sum up, application of organic manure and using legume crops is thought to increase the soil organic matter and improve soil structure (Schjønning et al. 2002, Edmedaes 2003, Abrishamkesh et al. 2011, Talgre et al. 2012, Słowińska-Jurkiewicz et al. 2013).

Dry bulk density of soil did not significantly differ between the compared fertilization systems but it was lower in Norfolk rotation than in crop rotation without legumes (Table 2). Although the differences between fertilized treatments were relatively small, it is important to note that farmyard manure led to a decrease 0.03–0.09 Mg/m^3 in bulk density compared to control and mineral fertilization. Dry bulk density in all treatments was further lowered with addition of farmyard manure as it has improved the aggregation status. Similar findings were reported by Ekwue (1992).

The effect of fertilization and crop rotation systems on water content in soil was significant (Table 3). As can be seen, the soil moisture of plots fertilized with farmyard manure compared to plots with mineral fertilizers was higher in both crop rotations. The soil moisture was the lowest in unfertilized plots in crop rotation without legumes, and the highest with application of farmyard manure in Norfolk rotation.

The field water capacity (FWC) is an optimal water status for plant production because the water and air contents of the soil are considered to be ideal for crop growth. The greatest ability to retain water at the 5–10 cm depth for the water potential –0.01 MPa and –0.025 MPa (FWC) was shown by the soil fertilized with farmyard manure, whereas the smallest ability was exhibited by mineral fertilized and unfertilized treatments (Table 4).

In general, the differences in soil moisture retention with and without farmyard manure treatments increased in Norfolk rotation. An increase

Table 5. Relationship between chosen soil parameters and field water capacity (FWC)

Soil parameter	(FWC) correlation coefficient (r)
Soil dry bulk density	–0.580**
Wet mean weight diameter	+0.817**
Water stability of aggregates	+0.776**

**significant at 1% probability level

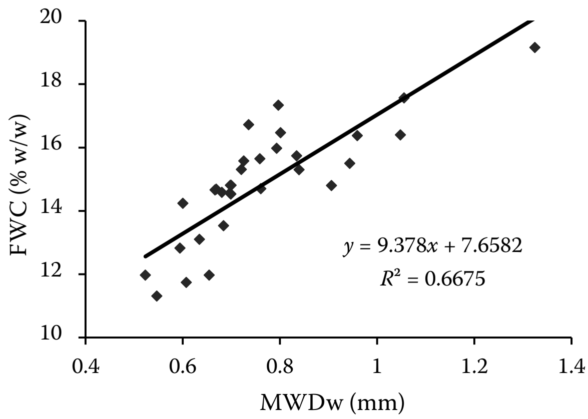

Figure 1. Relationship between wet mean weight diameter of aggregate (MWDw) and field water capacity (FWC)

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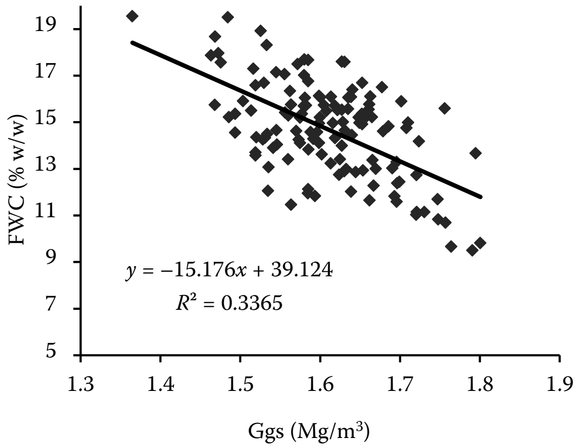

Figure 2. Relationship between dry bulk density (Ggs) and field water capacity (FWC)

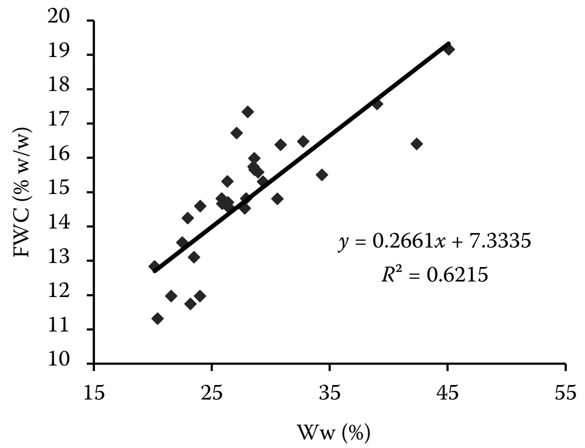

Figure 3. Relationship between water stability of aggregates (Ww) and field water capacity (FWC)

of water holding capacity of soils after application of farmyard manure or other organic fertilizers has been reported by other authors (Franzluebbers 2002, Singh et al. 2007, Suwara 2010).

To assess the possible field water capacity to dry bulk density and the soil structure parameters, data from the both experiments were correlated (Table 5, Figures 1–3).

Soil field water capacity was significantly (at $P < 0.01$, $n = 32$) correlated with mean weight diameter of resistant aggregate and water stability of aggregates. A correlation between the dry bulk soil density and water properties of soil was also proved.

Soil physical properties were more favourable in Norfolk rotation than in crop rotation without legumes. Long-term application of farmyard manure induced a significant increase in the water stability of aggregates and field capacity.

To sum up, the 54-year application of farmyard manure and use of red cover in crop rotation resulted in the lower soil bulk density, higher resistance of soil aggregates and field water capacity in comparison with unfertilized and mineral treatments. The application of mineral fertilizers without farmyard manure did not cause significant differences in soil structure, soil bulk density and water storage compared to unfertilized treatments.

The effect of different fertilization on water content was related to bulk density and soil structure stability. Decreased soil structure stability and an increased bulk density had a negative influence on field water capacity. The increase of water stability of aggregates in treatments with farmyard manure and red clover leading to positive influence on field water capacity may make these systems more sustainable over the long-term.

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