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Original Research

Air-Dry and Water-Stable Soil Aggregate Distribution of Polish Chernozems Classified in Various Complexes of Agricultural Suitability

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Abstract

The objective of this study was quality estimation of air-dry and water-stable soil aggregate distribution in Polish Haplic Chernozems developed from loess. It was found that among the Chernozems classified in the particular complexes of agricultural suitability there were small differences in the content of air-dry aggregates with sizes of 0.25-10 mm. The distribution of air-dry aggregates in horizons Ap, A, and ABw was estimated as good or medium, while that in horizons Bw and Ck as medium or poor. In the Chernozems classified in the very good wheat complex and the good wheat complex the content of water-stable aggregates with sizes of 0.25-10 mm was significantly greater than in soils classified in the deficient wheat complex. The water-stable aggregate distribution in the Ap horizons of soils classified in the very good and good wheat complexes was estimated as good, and in the Ap horizons of soils of the deficient wheat complex as medium. In horizons A the distribution of water stable aggregates was assessed as medium, and in horizons ABw, Bw, and Ck as poor or very poor.

Keywords: Chernozems developed from loess, complexes of agricultural suitability, air-dry aggregate size distribution, water-stable aggregate size distribution

Introduction

Chernozems are commonly accepted to be the best soils in the world, and their largest areas are found in Eastern Europe, Asia, and North America. They were formed under the conditions of the continental climate, with a relative balance between precipitations and evapotranspiration under grass or forest-steppe vegetation. They are characterized by a deep black mollic humus horizon developed as a result of the turf process, which consists of biological accumulation of notable amounts of nitrogen-rich organic matter in the soil substrate, with participation of the soil fauna [1, 2]. As a result of intensive humification, organic-mineral complexes of humic acids with clay minerals formed in Chernozems, often fixed with calcium compounds, and the content of humus may amount to 5-8%. In Eastern Europe Chernozems developed from loess are considered to be relic soils whose genesis is subject to discussion [3-5]. In Poland those soils occupy only about 1% of the area of the country [6]. The Polish Chernozems differ from East European Chernozems by having a smaller depth of the humus horizon, a lower content of humus and carbonates, and a higher degree of acidification. The mollic horizon contains 2-3% of humus and has a well developed aggregate structure that can be assessed with the naked eye.

As a rule, subjection to field cultivation causes a deterioration of the structure of Chernozems. As a result of intensive agricultural use, Chernozems situated on loess slopes

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are prone to water and tillage erosion [7, 8]. According to the Polish classification [9], the intensity of the processes of erosion on inclined slopes determines the inclusion of soils in various soil quality classes and complexes of agricultural suitability. Chernozems classified in the particular complexes of agricultural suitability may differ in their physical properties, including the quality of their structure. Intensive field cultivation (and especially excessive crumbling), kneading with tractor wheels, application of monoculture of cereals, and insufficient organic fertilization cause a deterioration of soil structure [10, 11]. Deterioration of the quality of aggregate size distribution and water stability of aggregates of soils of various genetic types on cultivated fields is indicated by the results of studies based on laboratory analyses [12, 13]. The objective of this study was to compare and estimate the quality of air-dry and water stable soil aggregate distribution of Polish Haplic Chernozems developed from loess, classified in various complexes of agricultural suitability.

Material and Methods

A field study on Chernozems developed from loess was conducted in 2008-11. For the study 4 pedons each were selected, representing three complexes of agricultural suitability of arable soils: a very good wheat complex (1), a good wheat complex (2), and a deficient wheat complex (3). The study comprised a total of 12 soils under winter wheat cultivation, situated in various mesoregions of Poland [14]:

a) Chernozems classified into very good wheat (1) complex of agricultural suitability and I-II valuation class, Nos.: 1 – Bidziny, 2 – Grochocice (Sandomierz Upland), 3 – Żulice, and 4 – Łykoszyn (Sokal Plateau)
b) Chernozems classified into good wheat (2) complex of agricultural suitability and IIIa valuation class, Nos.: 5 – Zajączkowice, 6 – Prusinowice (Sandomierz Upland), 7 – Kryszyn, and 8 – Telatyn (Sokal Plateau)
c) eroded Chernozems classified into deficient wheat (3) complex of agricultural suitability and IIIb valuation class, Nos.: 9 – Franusin, 10 – Wasylów, 11 – Radostów (Sokal Plateau), and 12 – Kułakowice (Horodło Plateau)

The Chernozems selected for the study were situated on private farms, where the share of cereals in crop rotation was most often 75%. The soils were characterized by a low level of organic fertilization, consisting mainly in ploughing-over of straw. The level of mineral fertilization applied varied, with a dominance of nitrogen fertilizers, while liming was applied only rarely.

Soil samples for laboratory analyses were collected in August, when wheat was in the phase of full ripeness, or shortly after its harvest. The samples were handled in amounts of 1.5-2 kg, from four horizons in the pedons, at depths of 0-25 cm (Ap horizon), 25-50 cm (horizons A or ABw), 50-75 cm (horizons A, Bw, or Ck), and 75-100 cm (horizons ABw, Bw or Ck) [6]. These samples were taken relatively dry to minimize vulnerability to disturbance. The largest clods were gently crumbled by hand along their natural failures immediately after sampling. Soil samples have been transported in rigid containers as gently as possible to avoid compression and breakdown of aggregates [15]. Drying of aggregates was done in the laboratory at room temperature (20ºC) to the air-dry state. Soil subsamples were oven-dried (105ºC) to determine the water content at the time of sampling.

The texture of the soils was determined with the areometric method of Casagrande as modified by Prószyński, separating the sand fraction on sieves with mesh sizes of 0.5, 0.25, and 0.1 mm. The particle size groups were determined in accordance with the classification of the Polish Society of Soil Science of 2008 [6]. The content of organic carbon was assayed using the analyzer Vario Max CNS Elementar, at the Central Laboratory of Chemical Analyses, IUNG, in Puławy. $CaCO_3$ content was determined with the Scheibler apparatus, and soil pH in 1 mol $KCl \cdot dm^{-3}$ was measured potentiometrically using a combined electrode.

The aggregate size distribution of the soils ($kg \cdot kg^{-1}$) was determined with the method of screening in air-dry state, using a sieve shaker machine and set of sieves with mesh sizes of 10, 7, 5, 3, 1, 0.5, and 0.25 mm, for soil weighed portions of 500 g, in two replications. Aggregates have been sifted for 1 minute. The aggregates remaining on each sieve were weighted and the proportion of each fraction has been calculated [16].

The content of water-stable soil aggregates ($kg \cdot kg^{-1}$) was determined with the method of screening in water, with the use of the modified Baksheiev apparatus made at the Institute of Agrophysics, Polish Academy of Sciences in Lublin. Weighed portions of soil with mass of 25 g were used (in 4 replications), composed of air-dry aggregates proportionally to their distribution according to size. The weighed portions of soil were placed in a set of sieves with mesh size of 7, 5, 3, 1, 0.5, and 0.25 mm. The aggregates were wetted through capillary rise, and then they were immersed in distilled water. The time of the water screening resulting from movement of the sieves was 12 minutes. Next, the particular fractions of water-stable aggregates (7-10, 5-7, 3-5, 1-3, 0.5-1, and 0.25-0.5 mm) were moved onto filter paper, dried at room temperature, and weighed. Wet-aggregate size distribution was expressed as a proportion of stable macroaggregates 0.25-10 mm and microaggregates <0.25 mm on the initial sample weight without correcting for sand [17].

The results obtained for the content of the particular fractions of dry and water stable aggregates were summed up and compiled in Tables 2 and 3. On the basis of the screening, the mean weight diameters of air-dry (MWD_{dry}) and water stable (MWD_{wet}) aggregates were calculated without correcting for sand according to van Bavel [16].

The results were subjected to analysis of variance with the use of double classification, in the completely random design, by means of the program STATISTICA 7 PL. The significance of differences obtained was verified with the Tukey test. Calculation was also made of the coefficients of

Table 1. Soil texture and some properties of Chernozems (range of values from 4 pedons).

Complex	Layer – depth (cm)	Horizons	% fraction with diameter in mm			$C_{org.}$ ($g\cdot kg^{-1}$)	$CaCO_3$ ($g\cdot kg^{-1}$)	pH_{KCl}
			2-0.05	0.05-0.002	<0.002			
1	0-25	Ap	12-14	74-78	8-12	11.2-18.3	0.0	4.7-5.4
	25-50	A	12-15	71-73	12-17	7.6-13.8	0.0	5.7-6.1
	50-75	A, Bw	12-14	70-73	14-17	1.6-12.0	0.0	6.2-6.4
	75-100	ABw, Bw	12-14	70-72	14-18	1.7-6.9	0.0-16.9	6.3-7.4
2	0-25	Ap	11-14	74-79	7-14	9.8-14.1	0.0-16.9	5.1-7.4
	25-50	A	11-15	66-74	15-19	5.2-7.9	0.0-65.5	6.0-7.6
	50-75	Bw, Ck	12-14	69-74	14-17	1.4-1.9	0.0-103.5	6.1-7.8
	75-100	Bw, Ck	12-15	71-74	14-15	0.6-1.7	0.0-128.9	6.8-7.9
3	0-25	Ap	11-16	71-76	13-17	7.0-9.7	0.0-31.7	6.6-7.5
	25-50	ABw	11-19	66-75	14-17	3.1-5.2	0.0-80.4	6.3-7.8
	50-75	Bw, Ck	12-20	67-73	13-16	1.2-2.5	1.3-90.8	7.3-7.8
	75-100	Ck	12-16	72-74	12-15	0.8-2.5	35.9-93.0	7.7-7.9

simple correlation (r) between the content of air-dry and water stable aggregates and the content of the individual particle size fractions $C_{org.}$ and $CaCO_3$.

Results

The studied Chernozems developed from loess were characterized by notable similarity of particle size distribution. The Ap horizons (0-25 cm) of soils classified in the very good wheat complex contained 12-14% of sand fraction (2-0.05 mm), 74-78% of silt (0.05-0.002 mm), and 8-12% of clay (<0.002 mm) (Table 1). The Ap horizons of soils classified in the deficient wheat complex had a higher content of clay (13-17%), similar to horizons A, ABw, Bw, and Ck in the layer of 20-100 cm (12-19%). In terms of particle size distribution, the soils studied constituted, most frequently, clayey silt or loamy silt.

The content of $C_{org.}$ in the Ap horizons of soils from the very good wheat complex was 11.2-18.3 $g\cdot kg^{-1}$, in the soils from the good wheat complex it was only slightly lower, and in the soils from the deficient wheat complex the lowest (7.0-9.7 $g\cdot kg^{-1}$) (Table 1). With depth into the pedons, the content of $C_{org.}$ decreased to 0.6-2.5 $g\cdot kg^{-1}$ in horizons Bw and C. The studied Chernozems classified in the very good wheat complex contained $CaCO_3$ at a depth of 75-100 cm or deeper (in horizons Bw and Ck). Whereas certain of the Chernozems classified in the good wheat and deficient wheat complexes contained calcium carbonate, also in horizons Ap and A. Reaction in the Ap horizons of soils classified in the very good wheat complex was acidic (pH 4.7-5.4), and in horizons A and ABw weakly acidic (pH 5.7-6.4). In the soils from the good wheat and the deficient wheat complexes reaction varied from acidic to alkaline (pH 5.1-7.9), and depended on the content of calcium carbonate. Soil moisture at the time of sampling was between 0.080 and 0.100 $kg\cdot kg^{-1}$. The effect of the water content at the time of sampling on the air-dry and water-stable soil aggregate distribution was slight.

The Chernozems under study were characterized by similar distributions of air-dry aggregates, in which macro-aggregates with sizes of 0.25-10 mm dominated over clods with sizes of >10 mm and micro-aggregates of <0.25 mm (Table 2). In the layer of 0-50 cm, i.e. in horizons Ap, A, and ABw, the content of air-dry aggregates with sizes of 0.25-10 mm was 0.566-0.613 $kg\cdot kg^{-1}$ and it decreased slightly in the layer of 50-75 cm. Only in a part of horizons Bw and Ck (in the layer of 75-100 cm) was it significantly lower (0.471-0.499 $kg\cdot kg^{-1}$). Similar trends were observed in the content of air-dry aggregates with sizes of 1-10 mm (0.415-0.475 $kg\cdot kg^{-1}$ in the layer of 0-50 cm and 0.356-0.432 $kg\cdot kg^{-1}$ in the layer of 75-10 cm). Among the individual fractions of micro-aggregates, in all the genetic horizons aggregates of 1-5 mm (0.209-0.291 $kg\cdot kg^{-1}$) dominated over aggregates of 5-10 mm and 0.25-1 mm. In the layer of 0-5cm the content of clods with sizes of >10 mm was, on average 0.356-0.368 $kg\cdot kg^{-1}$ and increased with depth in the pedons to 0.403-0.454 $kg\cdot kg^{-1}$. Whereas the content of micro-aggregates with sizes of <0.25 mm was very low in all the Chernozems (average of 0.041-0.063 $kg\cdot kg^{-1}$). As a result, in the 0-50 cm layer of the Chernozems the MWD_{dry} was, on average, 10.8-11.0 mm, and it increased to 12.6 mm in the layer of 75-10 cm. Only a few of the differences in the content of air-dry aggregates with sizes of 5-10 mm, 1-10 m and <0.25 mm among the Chernozems classified in the various complexes of agricultural suitability were statistically significant.

During wet screening, the air-dry soil aggregates disintegrated into finer fractions, including micro-aggregates with sizes of <0.25 mm. The content of water-stable aggre-

Table 2. Air-dry soil aggregate distribution (mean values from 4 pedons).

Complex (C)	Layer – depth (cm) (L)	Air-dry aggregate content of diameter in mm (kg·kg^{-1})							MWD$_{dry}$ (mm)
		>10	5-10	1-5	0.25-1	<0.25	Σ0.25-10	Σ1-10	
1	0-25	0.356	0.173	0.283	0.143	0.045	0.599	0.456	10.7
	25-50	0.380	0.193	0.274	0.121	0.032	0.588	0.467	11.4
	50-75	0.395	0.156	0.271	0.129	0.049	0.556	0.427	11.6
	75-100	0.454	0.150	0.222	0.127	0.047	0.499	0.372	13.2
2	0-25	0.363	0.184	0.275	0.154	0.024	0.613	0.459	10.8
	25-50	0.350	0.184	0.291	0.129	0.046	0.604	0.475	10.7
	50-75	0.401	0.186	0.264	0.104	0.045	0.554	0.450	12.0
	75-100	0.403	0.177	0.255	0.119	0.046	0.551	0.432	11.8
3	0-25	0.385	0.152	0.263	0.151	0.049	0.566	0.415	11.4
	25-50	0.338	0.193	0.273	0.143	0.053	0.609	0.466	10.4
	50-75	0.408	0.153	0.221	0.148	0.070	0.522	0.374	12.2
	75-100	0.447	0.147	0.209	0.115	0.082	0.471	0.356	12.9
Mean	0-25	0.368	0.169	0.274	0.150	0.039	0.593	0.443	11.0
	25-50	0.356	0.190	0.279	0.131	0.044	0.600	0.469	10.8
	50-75	0.401	0.165	0.252	0.127	0.055	0.544	0.417	11.9
	75-100	0.435	0.158	0.229	0.120	0.058	0.507	0.387	12.6
1	mean	0.396	0.168	0.262	0.131	0.043	0.561	0.430	11.7
2		0.379	0.182	0.271	0.127	0.041	0.580	0.453	11.3
3		0.395	0.162	0.241	0.139	0.063	0.542	0.403	11.7
LSD (α = 0.05):	layers L	0.068	0.024	0.045	n.s.	n.s.	0.064	0.060	1.8
	complexes C	n.s.	0.019	n.s.	n.s.	0.020	n.s.	0.047	n.s.
	interaction L×C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s. – non significant differences

gates with sizes of 0.25-10 mm was the highest in horizons Ap and A of the Chernozems studied, and it decreased gradually in horizons ABw, Bw, and Ck (Table 3). In the layer of 0-25 cm it was, on average, 0.571 kg·kg^{-1} and it was significantly higher than in the layers of 25-50 cm (0.467 kg·kg^{-1}), 50-75 cm (0.324 kg·kg^{-1}), and 75-100 cm (0.268 kg·kg^{-1}). Significantly higher in the Ap horizons than in the layer of 25-100 cm was, in particular, the content of water-stable aggregates with sizes of 1-10 mm (by 0.140-0.216 kg·kg^{-1}), including those of 5-10 mm and 1-5 mm. The content of aggregates with sizes of 0.25-1 mm was the highest in horizons A (0.371-0.401 kg·kg^{-1}), and the lowest in horizons Bw and Ck (0.171-0.284 kg·kg^{-1}). Whereas in horizons Bw and Ck, micro-aggregates with sizes of <0.25 mm, as products of disintegration of larger sized fractions, constituted as much as 0.716-0.829 kg·kg^{-1}, significantly more than in horizons Ap and A (0.365-0.475 kg·kg^{-1}). As a result, the MWD$_{wet}$ in the Ap horizons was, on average, 1.33 mm and it was significantly greater than in the subsurface horizons (0.33-0.59 mm).

In the Chernozems from the very good wheat complex the content of water-stable aggregates with sizes of 0.25-10 mm was significantly higher (by 0.063-0.115 kg·kg^{-1}), including stable aggregates of 0.25-1 mm (by 0.081-0.102 kg·kg^{-1}), than in soils from the good wheat complex and the deficient wheat complex, especially in the layer of 50-100 cm (Table 3). In turn, the soils from the good wheat complex had a significantly higher content of water-stable aggregates of 0.25-10 mm (by 0.052 kg·kg^{-1}) and MWD$_{wet}$ (by 0.12 mm) compared to the soils from the deficient wheat complex.

Analysis of correlation revealed that within the population of soils under study the content of air-dry aggregates did not show any significant correlations with the contents of individual particle size fractions and with the content of CaCO$_3$ (Table 4). That lack of significant correlations resulted from the uniform granularity of the soils studied, including small differences in the content of clay of <0.002 mm. Only the content of air-dry aggregates with sizes of 0.25-10 mm displayed a weak positive correlation with the content of C$_{org.}$ (r = 0.29).

Table 3. Water-stable soil aggregate distribution (mean values from 4 pedons).

Complex (C)	Layer – depth (cm) (L)	Water-stable aggregate content of diameter in mm (kg·kg^{-1})					Micro-aggregates <0.25 mm (kg·kg^{-1})	MWD$_{wet}$ (mm)
		5-10	1-5	0.25-1	Σ0.25-10	Σ1-10		
1	0-25	0.101	0.144	0.306	0.551	0.245	0.449	1.34
	25-50	0.003	0.121	0.401	0.525	0.124	0.475	0.55
	50-75	0.001	0.089	0.352	0.442	0.090	0.558	0.45
	75-100	0.003	0.055	0.292	0.350	0.058	0.650	0.37
2	0-25	0.090	0.244	0.301	0.635	0.334	0.365	1.48
	25-50	0.017	0.160	0.371	0.548	0.177	0.452	0.76
	50-75	0.006	0.037	0.219	0.262	0.043	0.738	0.33
	75-100	0.002	0.033	0.136	0.171	0.035	0.829	0.26
3	0-25	0.074	0.158	0.295	0.527	0.232	0.473	1.16
	25-50	0.008	0.082	0.238	0.328	0.090	0.672	0.45
	50-75	0.002	0.069	0.196	0.267	0.071	0.733	0.36
	75-100	0.003	0.066	0.215	0.284	0.069	0.716	0.37
Mean	0-25	0.088	0.182	0.301	0.571	0.270	0.429	1.33
	25-50	0.009	0.121	0.337	0.467	0.130	0.533	0.59
	50-75	0.003	0.065	0.256	0.324	0.068	0.676	0.38
	75-100	0.003	0.051	0.214	0.268	0.054	0.732	0.33
1	mean	0.027	0.102	0.338	0.467	0.129	0.533	0.68
2		0.029	0.118	0.257	0.404	0.147	0.596	0.71
3		0.022	0.094	0.236	0.352	0.116	0.648	0.59
LSD (α = 0.05)	layers L	0.012	0.034	0.037	0.051	0.040	0.051	0.13
	complexes C	n.s.	n.s.	0.030	0.040	n.s.	0.040	0.11
	interaction L×C	0.018	0.055	0.059	0.080	0.063	0.080	0.21

n.s. – non significant differences

The content of all water-stable aggregate fractions and the values of MWD$_{wet}$ correlated closely and positively with the content of C$_{org.}$ (r = from 0.57 to 0.79) (Table 4). The highest value of the coefficients of correlation was characteristic of the sum of stable aggregates with sizes of 0.25-10 mm (r = 0.79). In addition, the content of water-stable aggregates of 5-10 mm, 1-5 mm, 1-10 mm, and 0.25-10 mm, and the values of MWD$_{wet}$, were closely positively correlated with the content of silt (r = from 0.40 to 0.61). At the same time, a negative correlation was noted between the content of stable aggregates of 5-10 mm, 1-5 mm, 1-10 mm and MWD$_{wet}$ and the content of clay (r = from -0.57 to -0.64). Those relations resulted from greater content of silt and smaller content of clay in horizons Ap and A, characterized by the greatest water stability of aggregates. Moreover, stable aggregates of 0.25-1 mm displayed a weak negative correlation with the content of sand and $CaCO_3$.

Discussion

The aggregate structure of soils is formed as a result of numerous physical, chemical, and biological processes. The main role in the formation of soil aggregates is that of physical phenomena: flocculation of clay minerals, cohesion of soil particles, alternating cycles of wetting-drying and freezing-thawing, mechanical compaction by plant roots, and that caused by the activity of soil fauna, especially earthworms. Organic agents stabilizing soil aggregates include microbiological and vegetable polysaccharides, plant roots, mycelium hyphae, and certain fungi [11, 18, 19]. The most stable binding agents include aromatic humic substances bound within soil aggregates with polyvalent cations Ca^{2+}, Mg^{2+}, Fe^{3+}, and Al^{3+}, and strongly sorbing polymers originating from resistant fragments of roots, mycelium hyphae, and bacterial cells. The processes of aggregation and aggregate stabilization have their own sea-

Table 4. Correlation coefficients (r) between content of granulometric fractions, $C_{org.}$, $CaCO_3$, and air-dry and water-stable aggregate content (n = 48).

Variable	Content of fractions (%)			$C_{org.}$ (g·kg^{-1})	$CaCO_3$ (g·kg^{-1})
	2-0.05 mm	0.05-0.002 mm	<0.002 mm		
Air-dry aggregates (kg·kg^{-1})					
>10 mm	-0.06	0.02	0.02	-0.21	0.06
5-10 mm	-0.06	-0.06	0.12	0.16	-0.08
1-5 mm	0.01	-0.11	0.12	0.24	-0.18
0.25-1 mm	0.07	0.17	-0.26	0.15	0.06
<0.25 mm	0.11	-0.01	-0.09	-0.21	0.16
Σ 0.25-10 mm	0.02	-0.02	0.01	0.29*	-0.12
Σ 1-10 mm	-0.01	-0.11	0.14	0.24	-0.16
MWD_{dry}	-0.06	-0.01	0.06	-0.20	0.02
Water-stable soil aggregates (kg·kg^{-1})					
5-10 mm	-0.01	0.53**	-0.62**	0.63**	-0.18
1-5 mm	-0.11	0.57**	-0.57**	0.58**	-0.14
0.25-1 mm	-0.29*	-0.03	0.28	0.57**	-0.30*
Σ 0.25-10 mm	-0.23	0.40**	-0.27	0.79**	-0.30*
Σ 1-10 mm	-0.09	0.61**	-0.64**	0.66**	-0.17
MWD_{wet}	-0.08	0.59**	-0.63**	0.71**	-0.21

*significance level α = 0.05, **significance level α = 0.01

sonal dynamics related to changes in soil moisture and temperature and also with the activity of soil micro-organisms. The lowest stability of soil aggregates is observed toward the end of winter and the highest in summer.

The research results presented here revealed a slight variation in the air-dry aggregate distribution among the Chernozems classified in the individual complexes of agricultural suitability, and only a little more pronounced variation among the horizons and layers within the pedons. The greater content of air-dry aggregates with sizes of 0.25-10 mm in horizons Ap and A compared to horizons ABw, Bw, and Ck was a result of higher content of $C_{org.}$ [18, 19]. Whereas the lower content of $C_{org.}$ in horizons Bw and Ck was conducive to stronger clodding of the soil mass. In the case of soils with similar particle size distribution, differences in the aggregate composition are caused by differences in the content of organic matter, diversified cultivation treatments, and crop rotations. After the pre-sowing tillage the aggregate composition of Ap horizons is always more disintegrated, but after a few months, under the effect of rainfall and gravity, the aggregates of those fragments get joined again into coarser fractions.

A favorable aggregate composition of soil is characterized by a very high content of air-dry macro-aggregates with sizes of 0.25-10 mm, and especially those of 1-10 mm, with a small content of clods with sizes of >10 mm and micro-aggregates of <0.25 mm [11, 20-22]. Such an aggregate distribution creates suitable conditions for the germination, emergence, and growth of plants, has a beneficial effect on the length of plant roots and on the density of the canopy, and provides the soil with a favorable content of mesopores with diameters 0.2-20 μm for the retention of water usable for plants, and a suitable content of macropores of >20 μm that determine the hydraulic conductivity and the air capacity and permeability of soil [23-25].

To estimate the quality of aggregate distribution of the Polish Chernozems the results obtained were compared with the results of studies by other authors and on other types of soils. The most favorable air-dry aggregate distribution is characteristic of soils under natural forest or grassland vegetation (steppe or meadow) [12, 13, 22]. Russian Chernozems are characterized by an exceptionally high content of air-dry aggregates with sizes of 0.25-10 mm, which is due to their high humus content. According to Kuznetsova [19], the content of aggregates with sizes of 0.25-10 mm in non-cultivated Typical and Leached Chernozems was 0.850-0.950 kg·kg^{-1}, and the content of clods of >10 mm was only 0.050-0.100 kg·kg^{-1}. Ćirić et al. [13], studying soils in northern Serbia, observed a favorable aggregate distribution of Chernozems which contained, on average, 0.841 kg·kg^{-1} of aggregates of 0.25-10 mm (including 0.607 kg·kg^{-1} of aggregates of 1-10 mm), and only 0.091 kg·kg^{-1} of clods of >10 mm. According to those authors, a similarly favorable aggregate distribution was

Table 5. Classification of air-dry aggregate size distribution of Polish Chernozems.

Air-dry aggregate size distribution	Air-dry aggregate content of diameter (kg·kg^{-1})			MWD$_{dry}$ (mm)
	0.25-10 mm	1-10 mm	Clods >10 mm	
Very good	>0.700	>0.550	<0.250	<9.0
Good	0.600-0.700	0.450-0.550	0.250-0.350	9.0-11.0
Medium	0.500-0.600	0.400-0.450	0.350-0.450	11.0-13.0
Poor	0.400-0.500	0.300-0.400	0.450-0.550	13.0-16.0
Very poor	<0.400	<0.300	>0.550	>16.0

observed in Gleysols (0.808 kg·kg^{-1} of aggregates of 0.25-10 mm and 0.170 kg·kg^{-1} of clods of >10 mm) and in Fluvisols (0.721 kg·kg^{-1} of aggregates of 0,25-10 mm and 0.197 kg·kg^{-1} of clods of >10 mm).

According to Pranagal [12], in the 0-20 cm layer of a Polish Haplic Chernozem under forest vegetation air-dry aggregates of 1-10 mm constituted 0.591-0.626 kg·kg^{-1}, under grasslands 0.528-0.631 kg·kg^{-1}, and in an arable field 0.473-0.516 kg·kg^{-1}. Whereas the content of clods of >10 mm in the forest was 0.056-0.110 kg·kg^{-1}, on the grasslands 0.222-0.300 kg·kg^{-1}, and in then arable field 0.357-0.399 kg·kg^{-1}. Compared to East European Chernozems, the Chernozems of Poland tend to clod to a greater extent, due to their lower content of organic matter. The same author observed that a Haplic Fluvisol with the particle size distribution of silt and with a similar content of C$_{org.}$ under forest contained 0.544-0.619 kg·kg^{-1} of air-dry aggregates with sizes of 1-10 mm, and only 0.047-0.131 of clods of >10 mm. The Fluvisol under grasslands contained 0.517-0.553 kg·kg^{-1} of aggregates of 1-10 mm and 0.173-0.310 kg·kg^{-1} of clods of >10 mm, while in an arable field it had 0.413-0.430 kg·kg^{-1} of aggregates of 1-10 mm and 0.312-0.313 kg·kg^{-1} of clods [12]. In another study [26] Fluvisols formed from silty alluvia contained in their Ap horizon 0.593-0.743 kg·kg^{-1} of air-dry aggregates of 0.25-10 mm (incl. 0.443-0.542 kg·kg^{-1} of aggregates of 1-10 mm) and 0.213-0.385 kg·kg^{-1} of clods of >10 mm, and their MWD$_{dry}$ was 5.9-10.3 mm. In turn, Phaeozems developed from silty formations contained, in their horizons Ap and A, 0.524-0.592 kg·kg^{-1} of aggregates of 0.25-10 mm and 0.342-0.415 kg·kg^{-1} of clods of >10 mm, and their MWD$_{dry}$ was 11.1-13.0 mm [27].

According to Kuznetsova [22], the optimum aggregate distribution of arable Russian Typical and Leached Chernozems is considered to be such in which the content of aggregates of 0.25-10 mm is 0.700-0.800 kg·kg^{-1}, and the content of clods of >10 mm is 0.200-0.300 kg·kg^{-1}. In turn, the aggregate distribution is considered to be acceptable when the content of aggregates of 0.25-10 mm is 0.500-0.700 kg·kg^{-1} and content of clods of >10 mm 0.300-0.500 kg·kg^{-1}. Whereas aggregate distribution is considered to be critical when aggregates of 0.25-10 mm constitute <0.500 kg·kg^{-1} and clods >0.500 kg·kg^{-1}.

Comparing the results obtained with literature data [12, 13, 22, 25, 28], an original classification of air-dry aggregate distribution of Polish Chernozems was developed (Table 5). The distribution was considered to be good if aggregates of 0.25-10 mm constitute >0.700 kg·kg^{-1} and clods of >10 mm below 0.250 kg·kg^{-1}, and very poor – when the content of aggregates of 0.25-10 mm is <0.400 kg·kg^{-1}, and that of clods of >10 mm is above 0.550 kg·kg^{-1}.

According to that classification, the aggregate distribution of horizons Ap and A (in the layer of 0-50 cm) of Chernozems included in the good wheat complex and horizons ABw (25-50 cm) of the deficient wheat complex was estimated as good. The distribution of horizons Ap and A of soils from the very good wheat complex was classified on the border between good and medium, while horizons ABw, Bw, and Ck in the layer of 75-100 cm had medium or poor aggregate distribution (Table 5).

The research results presented here demonstrated a significantly higher content of water-stable aggregates with sizes of 0.25-10 mm in horizons Ap and A of the Chernozems studied, as compared to horizons Bw and Ck (in the layer of 75-100 cm). This results from the notably greater content of C$_{org.}$, including organic compound stabilizing soil aggregates, and those results are in agreement with results of other studies [12, 19]. The higher content of water-stable aggregates of 0.25-10 mm and 1-10 mm observed in horizons Ap of soils of complex two compared to those of complex one resulted from the appearance of a mix of legumes and grasses in the crop rotations on soils Nos. 6 and 7 in preceding years. They exerted a favorable effect on the stability of soil aggregates [11, 29]. Whereas in the Ap horizons of Chernozems from the deficient wheat complex situated on slopes, water and tillage erosion causes a decrease in the content of organic matter and, consequently, a reduction in the content of water-stable soil aggregates, especially those with sizes of 1-10 mm [30].

As in the case of air-dry aggregate distribution, also the highest water stability of aggregates is found under forest, steppe, or meadow vegetation [12, 22, 29]. In non-cultivated Typical and Leached Chernozems the content of water stable aggregates with sizes of >0.25 mm was 0.720-0.860 kg·kg^{-1}, including aggregates of >1 mm at 0.450 kg·kg^{-1} [22]. According to Balashov and Buchkina [31], fallowed Haplic Chernozem with particle size distribution of clayey loam contained 0.901±0.094 kg·kg^{-1} of water stable aggregates, and under agricultural use for 75 years – 0.708±0.082 kg·kg^{-1}.

Table 6. Classification of wet aggregate size distribution of Polish Chernozems.

Wet aggregate size distribution	Water-stable aggregate content of diameter (kg·kg^{-1})		Microaggregates <0.25 mm (kg·kg^{-1})	MWD$_{wet}$ (mm)
	0.25-10 mm	1-10 mm		
Very good	>0.650	>0.400	<0.350	>2.0
Good	0.550-0.650	0.200-0.400	0.350-0.450	1.2-2.0
Medium	0.450-0.550	0.100-0.200	0.450-0.550	0.8-1.2
Poor	0.350-0.450	0.050-0.100	0.550-0.650	0.4-0.8
Very poor	<0.350	<0.100	>0.650	<0.4

Pranagal [12] observed that a Polish Haplic Charnozem in the layer of 0-10 cm under forest contained 0.747 kg·kg^{-1} of water-stable aggregates of 0.25-10, on a grassland 0.635 kg·kg^{-1}, and in an arable field 0.393 kg·kg^{-1}. The content of stable aggregates of 1-10 m under forest was 0.607 kg·kg^{-1}, on a grassland 0.432 kg·kg^{-1}, and in an arable field as little as 0.055 kg·kg^{-1}. Also, the value of MWD$_{wet}$ under forest was 2.3 mm and it was higher than on the grassland (1.7 mm) and I, the arable field – 0.4 mm. Still higher water stability of aggregates was displayed by a Haplic Fluvisol which, in the layer 0-20 cm under forest contained 0.771-0.728 kg·kg^{-1} of stable aggregates of 0.25-10 mm, 0.687-0.708 kg·kg^{-1} under grassland, and 0.583-0.618 kg·kg^{-1} in an arable field. The content of stable aggregates of 1-10 mm was 0.524-0.604 kg·kg^{-1} under forest, 0.500-0.537 kg·kg^{-1} on grassland, and 0.346-0.390 kg·kg^{-1} in arable field. As a result, the value of MWD$_{wet}$ was the highest under forest, at 2.2-2.6 mm and on the grassland (2.0 mm), compared to the arable field (1.5-1.7 mm) [12]. In another study, Fluvisols with the particle size distribution of silts contained 0.653-0.752 kg·kg^{-1} of water stable aggregates of 0.25-10 mm, including 0.307-0.484 kg·kg^{-1} of aggregates of 1-10 mm, and their MWD$_{wet}$ was 1.6-2.3 mm [26]. In turn, Phaeozems developed from silt formations contained, in the Ap horizon, 0.695-0.720 kg·kg^{-1} of water-stable aggregates of 0.25-10 mm, and their MWD$_{dry}$ was 1.1-1.7 mm [27].

For cultivated Russian typical and leached Chernozems, a content of stable aggregates of >0,25 mm equal to 0.400-0.600 kg·kg^{-1} is considered to be optimum, 0.300-0.400 kg·kg^{-1} as acceptable, and <0.300 kg·kg^{-1} as critical [22]. Comparing the results obtained with literature data [12, 22, 26-28], an original classification of water-stable aggregate distribution of Polish Chernozems was developed (Table 6). The distribution was classified as very good if stable aggregates with sizes of 0.25-10 mm constitute >0.650 kg·kg^{-1}, aggregates of 1-10 mm >0.400 kg·kg^{-1}, a the value of MWD$_{wet}$ is >2.0 mm. Whereas, the distribution is very poor of the content of water stable aggregates with sizes of 0,25-10 mm constitutes <0.350 kg·kg^{-1}, that of aggregates of 1-10 mm is <0.050 kg·kg^{-1}, and MWD$_{wet}$ is <0.4 mm.

According to that classification, the water-stable aggregate distribution in horizons Ap of Chernozems included in the very good and good wheat complexes was estimated as good, and in the Ap horizons of soils from the deficient wheat complex as medium. In the A horizons the distribution of water-stable aggregates was estimated as medium, and in horizons ABw, Bw, and Ck as poor or very poor (Table 6).

To prevent deterioration of the air-dry and water-stable aggregate distribution in Chernozems it is necessary to apply regular organic fertilization, especially with FYM [32-34] or compost [10, 35], as well as crop rotations with legumes and grasses, whose roots have a stabilizing effect on aggregate distribution and on water stability of aggregates [11, 29], and provide protection against water erosion.

Conclusions

1. Horizons Ap and A of the Polish Chernozems developed from loess were characterized by a significantly higher content of air-dry aggregates with sizes of 0.25-10 mm, including aggregates of 1-10 mm, compared to horizons Bw and Ck in the layer of 75-100 cm, and a lower content of clods of >10 mm and a lower value of MWD$_{dry}$.
2. Among the Chernozems classified in various complexes of agricultural suitability there were infrequent significant differences in the air-dry aggregate distribution, due to similar particle size distribution and slight differences in the content of C$_{org.}$.
3. The air-dry aggregate distribution in horizons Ap, A, and ABw of the Chernozems was estimated as good or medium, and in horizons Bw and Ck as medium or poor.
4. The content of water-stable aggregates with sizes of 0.25-10 mm, and especially of 1-10 mm, and the values of MWD$_{wet}$ in horizons Ap and A of the Chernozems studied were significantly higher than in horizons ABw, Bw, and Ck. The content of all water-stable aggregate fractions and the values of MWD$_{wet}$ were closely positively correlated with the content of C$_{org.}$ and with the content of silt.
5. In the Chernozems classified in the very good and good wheat complexes the content of stable aggregates with sizes of 0.25-10 mm, including those of 0.25-1 mm, was significantly higher than in soils from the deficient wheat complex.

6. The distribution of water-stable aggregates in the Ap horizons of Chernozems classified in the very good and good wheat complexes was estimated as good, and in the Ap horizons of soils classified in the deficient wheat complex as medium. In horizons A the distribution of stable aggregates was estimated as medium, and in horizons ABw, Bw, and Ck as poor or very poor.

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