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Assessment of the structural-aggregate composition of podzolized chernozem under various agrogenic impacts and post-agrogenic state

V. Bulgakov[1], I. Gadzalo[2], V. Kropivnyi[3], O. Demydenko[4], I. Holovach[1], Ye. Ihnatiev[5,6], O. Trokhaniak[1] and J. Olt[5,*]

[1]National University of Life and Environmental Sciences of Ukraine, 15 Heroyiv Oborony Str., UA03041 Kyiv, Ukraine
[2]National Academy of Agrarian Sciences of Ukraine, 9 Mykhailo Omelyanovych-Pavlenko Str., UA01010 Kyiv, Ukraine
[3]Central Ukrainian National Technical University, University Ave., 8, UA25006 Kropivnitskyi, Kirovograd region, Ukraine
[4]Cherkasy State Agricultural Experimental Station National Scientific Centre, Institute of Agriculture of NAAS of Ukraine, 13 Dokuchaieva Str., Kholodnianske village, Cherkassy district, UA20731 Cherkassy region, Ukraine
[5]Estonian University of Life Sciences, Institute of Forestry and Engineering, 56 Kreutzwaldi Str., EE51006 Tartu, Estonia
[6]Dmytro Motornyi Tavria State Agrotechnological University, 66 Zhukovsky Str., UA69600 Zaporizhzhia, Ukraine
[*]Correspondence: jyri.olt@emu.ee

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Abstract. Identify the main patterns of transformation and establish normative parameters of changes in the structural and aggregate composition of low-humus podzolized chernozem (type of soil, known as 'chernozem' in Ukrainian, which translates to 'black soil') in the Central Forest-Steppe of Ukraine in the transition period to the no-till system and minimal tillage in the agrocenosis of 5-field grain generally accepted approaches to assessing soil structure and modern statistical methods of compiling information analysis data. The generally accepted research methods were used: field, laboratory, mathematical methods, comparative and computational. The study uses fractal comparative analysis, which is a sensitive tool for assessing the distribution of structural units and water-stable aggregates in the soil. Over the past 6 years, the experimental plots have been organized with a 5-field grain-row crop rotation using three different primary tillage systems: systematic plowing, surface tillage, and transitional tillage (minimal tillage on the background of systematic plowing six years ago). It was found that the structural-aggregate state of the 0–30 cm layer of Chernozem under surface tillage was in better condition in terms of aggregate water stability over the seasonal cycle and provided better conditions for further transition to the no-till system in crop rotation compared to surface tillage after systematic plowing. According to fractal indicators, the state of water-resistant structure in the spring is assessed as unstable, although the surface treatment of qualitative and quantitative indicators of water resistance is better compared to plowing. In the summer, a fractal assessment of the state of the waterproof structure showed that regardless of the method of tillage, its condition has deteriorated to a greater extent. Thus, the fractal dimension was at the level of $D > 2$, which indicates the edge of the unstable state of the waterproof structure, but the Hurst index was $H \leq 0$, which indicates the process of destruction of waterproof aggregates. Based on the definitions, we can say that from the systematic application of surface tillage agrophysical condition of 0–30 cm layer of chernozem in terms of structural condition and water resistance of the structure was in better condition compared to plowing and transitional tillage, which should be regarded as the end of the transition period (6 years) before the application of the No-till system in unchanged design in 5-field crop rotation.

Key words: fractal dimension, plowing, structural condition, surface treatment, water resistance.

INTRODUCTION

The prolonged intensive use of Chernozems **(**type of soil, known as ‘chernozem’ in Ukrainian, which translates to ‘black soil’) in the Central Forest-Steppe of Ukraine leads to the degradation of agroecosystems, especially concerning Chernozems (Balyuk et al., 2010). This results in dehumification and overall deterioration of the complex agrophysical properties of valuable zonal soils - Chernozems, leading to a decrease in humus content, destruction of soil structural aggregates, compaction, and the development of erosion processes. A necessary measure for rehabilitating degraded Chernozems is primarily the restoration of their structural-aggregate state (Medvediev, 2008; Demydenko, 2013; Blanco-Canqui & Ruis, 2013). The soil structure is influenced by the global carbon cycle (Demydenko & Velichko, 2013; Bardgett et al., 2014; Jacobs et al., 2009), fertility, environmental conditions, and humus regimes in plowed Chernozems (Jordan et al., 2010; Modak et al., 2010; Nandan et al., 2019; Copec et al., 2015). Soil structure refers to the form and size of structural disparities and water-resistant aggregates into which soil disintegrates under agrogenic impact, characterized by the form and degree of development of structural disparities. ‘Agrogenic soils’ are soils that are influenced by human agricultural activities. They are formed and altered under the impact of various agronomic practices such as plowing, sowing, fertilization, irrigation, drainage, and others (Volungevicius et al., 2018; Rieznik et al., 2021). One of the most important indicators of structure is its water resistance - the ability not to disintegrate under moisture (Zhang et al., 2015; Lampurlanes et al., 2016; Castellini et al., 2019).

In soil physics, soil structure is quantitatively evaluated based on the distribution of aggregates (air-dry and in water) according to their sizes. The first quantitative indicator of structure is the content of air-dry aggregates of different sizes. Another indicator of structure is its stability to external influences, among which moisture influence is most important (Dudchenko et al., 2014). The simplest express method for quantitative assessment of structure is sieving air-dry soil through a set of sieves of different sizes or shaking sieves in water during wet sieving. However, the adopted procedures for evaluating the results of wet and dry sieving are usually aimed at reducing all data to a single indicator. Often, the structural coefficient is used - the ratio of aggregates from dry sieving with sizes of 10(7)–0.25 mm to the sum of structural disparities > 10 mm and < 1 mm. For the quantitative characterization of structure, the content of agriculturally valuable aggregates in the soil is also applied, with different sources providing different size boundaries for this fraction: most consider fractions of

7–0.25 mm or 10–0.25 mm as agriculturally valuable aggregates (Kachmar et al., 2019). Additionally, indicators of the average size of aggregates are used, such as their mean weighted diameter and mean geometric diameter. According to the described approaches, only one value is accepted from a fairly large amount of data (size distribution), which complicates a detailed characterization of soil structure (Medvediev, 2016).

For a more detailed characterization of soil structure, in addition to the results of dry sieving, other data are commonly used: relative water resistance of aggregates, distribution of water-resistant aggregates by size, microaggregates, and granulometric elements in the soil. The potential of mathematical description of aggregate composition as a distribution, in this case, a lognormal distribution, has been previously demonstrated (Medvediev, 2008; Burdina & Priss, 2016).

In modern soil physics, soil structure is modeled using geometric models, which can be broadly divided into two classes - regular and irregular models. In regular models of soil structure, the principle of complete similarity of parts of the fissured space to capillary-porous bodies is implemented, and calculations of differential porosity are based on geometry (Backhaus, 2008; Cantón et al., 2009). A common feature of regular models is the complete exclusion of randomness, disruption of order, and chaotic organization of soil disparities and their spatial arrangement. Irregular models of soil structure include models based on similarity concepts. They extensively utilize representations of fractal geometry and fractal dimension of soil porous space (ASTM D6913-04, 2009; State Standard of Ukraine, 2008; Chefetz et al., 2002; Yermakov et al., 2021). Fractal models of soil structure are based on chaos theory, of which fractals are a part (Ahmadi et al., 2011; Daraghmeh et al., 2009).

The effective assessment of the structural-aggregate state of chernozems requires regular comprehensive, interdisciplinary research on the agroecological functions of soils and closely related soil genetic and dynamic properties. Soil genetic, stable properties include: the degree of manifestation of soil-forming processes, structural-aggregate, fractional and group composition of humus, granulometric and mineralogical composition, and soil profile thickness. These properties reflect the potential ability of soils to function within agroecosystems. Dynamic, manageable soil properties include numerous agrochemical, physical, physicochemical, and biological parameters and processes (Dehtyarov et al., 2012).

In recent decades, the problem associated with the deterioration of the structural-aggregate state of plowed chernozems has intensified. Therefore, the study of the structural-aggregate state of plowed chernozems in the Central Forest-Steppe under different land use systems with varying levels of agrogenic pressure is of great importance for assessing the stability of soil structure to intensive agrogenic influence (Ivanovs et al., 2020; Volkohon & Moskalenko, 2020).

The structural-aggregate state influences both the overall agrophysical condition of chernozem and its fertility as a whole. However, the structural state of chernozem depends on many factors, namely the cultivated crop, predecessor, soil tillage system, humus content, application of organic and mineral fertilizers, calcium content, as well as agrogenesis of the soil differences themselves. Research on the modern agromachinery (Bulgakov et al., 2017; Bulgakov et al., 2019; Bulgakov et al., 2020; Kägo et al., 2021; Olt et al., 2024) and agrogenic influence on the structure of chernozem is relevant, especially during the transition to minimum tillage systems and No-till systems, in modern soil-climatic conditions of the Forest-Steppe region of Ukraine.

The aim of the research is to identify the main patterns of transformation and establish normative parameters of change in the structural-aggregate composition of low-humus podzolized chernozem in the Central Forest-Steppe of Ukraine during the transition period to the No-till system and minimum tillage in a 5-field crop rotation through the application of a comprehensive methodological approach. This approach includes commonly accepted methods for assessing soil structure and modern statistical methods for data analysis. Existing statistical methods and approaches allow for maximum utilization of the amount of data obtained with minimal loss of information. One of the most common approaches is the Principal Component Analysis (PCA) method, cluster analysis, non-parametric statistics, and fractal analysis.

MATERIALS AND METHODS

The research was conducted at the field experimental station of the Cherkasy State Agricultural Research Station of the National Scientific Center ‘Institute of Agriculture of the National Academy of Agrarian Sciences’ from 2016 to 2021. The soil studied is a strongly degraded low-humus medium loamy podzolized chernozem on carbonate molehill loess. (Polupan et al., 2005), it is also known as Chernic Phaeozems (Hyperhumic, Siltic, Calcaric, Cutanic, Episiltic, Sodic) according to WRB, 2022. In the plow layer (0.22–0.25 m), the humus content ranges from 2.76% to 3.03% (according to the Tyurin method), the sum of absorbed bases ranges from 24.5 to 28.1 mg-eq per 100 g of soil, hydrolytic acidity ranges from 1.99 to 2.19 mg-eq per 100 g of soil, pH of the salt extract ranges from 5.56 to 6.31 - soil to water ratio 1:2.5 (FAO, 2021). The base saturation degree is between 92.8% and 93.3%, the content of exchangeable phosphorus forms (according to the Truog method) is 9.0 mg per 100 g of soil, and exchangeable potassium (according to the Brovkin method) is 12 mg per 100 g of soil.

Detailed description of morphological structure of profile of analyzed soil:

$A_{0\ 0-4}$ – sod, penetrated by plant roots;

$A_{1si\ (t)\ 5-47}$ – humus horizon, barely perceptibly eluvial, 5 YR 3/1, lumpy-powdery in structure, slightly dense, medium porosity, many plant roots, earthworm channels, filled burrows casts at the bottom of the horizon (5×6 cm), gradual transition in color;

$A_{2\ si\ (t)\ 48-82}$ – transitional horizon, 5 YR 6/2, lumpy-granular in structure, medium porosity, earthworm channels, the transition is faintly visible in color, the transition line is wavy;

$B_{1\ si\ (t)\ 83-123}$ – transitional horizon, 7.5 YR 6/2, granular-lumpy in structure, dense (compacted), a few roots, gradual transition in color, the transition line is wavy;

$B_{2\ (ca)\ 123-170}$ – loess, 7.5 YR 6/4, earthworm channels, infilled large burrows, layers of carbonates, carbonates in mold form;

$C_{ca\ 170-200}$ – pale brownish carbonate forest horizon.

The research was conducted in a field stationary experiment aimed at studying the productivity of a 5-field crop rotation, which included peas, winter wheat, corn, soybeans, and barley. The tillage system included: 1. Differentiated tillage based on plowing; 2. Differentiated tillage with deep chiseling in 2016 followed by surface tillage to a depth of 10–12 cm for all crops in the rotation over a period of 6 years; 3. Minimum tillage to a depth of 5–7 cm against the background of systematic plowing (transitional tillage). The fertilization system for all crops was $N_{75}P_{65}K_{82}$ + 6 t ha^{-1} of by-products (chopped straw of cereal crops).

The analysis of the structural composition was conducted in the 0–0.3 m soil layer under all crops of the 5-field crop rotation at depths of 0–0.2 m and 0.2–0.3 m with fivefold repetition. The structural state was studied together with determining the structure density. When conducting research, a standard sampling method, tools and methodology for determining indicators were used. The total humus content was determined by Tyurin's I.V. method in Simakov's M.V. modification (State standard of Ukraine, DSTU 4289:2004). The structural-aggregate composition was analyzed using the sieve method (ASTM D6913-04, 2009) in Savinov's N.I. modification according to (DSTU 4744:2007) (State Standard of Ukraine, 2008), and soil structure stability was determined by I.M. Baksheev's method.

Statistical calculations of the research results were conducted using the Analysis of Variance (ANOVA) method with the STATISTICA software, along with the application of non-parametric statistical methods, correlation analysis, factor analysis, and fractal analysis (Backhaus, 2008).

RESULTS AND DISCUSSUION

In the 6th year of performing surface tillage and plowing of podzolic chernozem, a new soil tillage method was introduced, where minimal tillage to a depth of 5–7 cm was carried out against the background of systematic plowing as a transitional tillage method. The main goal of introducing this new method was to determine the agrophysical ‘readiness’ of chernozem to transition to a No-till system from systematic no-till treatment and from minimal tillage against the background of systematic plowing. The variants of systematic plowing and surface tillage are necessary for the control comparison of changes in the agrophysical state and productivity of a 5-field grain crop rotation.

Fig. 1 shows the redistribution of structural aggregates within the agronomically valuable range. It was found that during the period of surface tillage, the content of structural aggregates sized 3–0.5 mm increased by 2.0%. This increase in content occurred at the expense of a decrease in the content of aggregates sized 0.5–0.25 mm, an increase in the content of aggregates sized 7–5 mm, and a decrease in the content of aggregates larger than 7 mm by 3.6%. Although the overall distribution pattern of structural aggregates remained nearly unchanged, as indicated by the exponential equation of structural aggregate distribution, which was significant (R^2 = 0.51–0.58), the regression coefficient for e varied between 0.37 and 0.43 (Table 4).

The determination of soil structure water stability in the 0–30 cm layer of chernozem showed that the number of water-resistant aggregates larger than 0.25 mm was 1.2 times higher under surface tillage compared to plowing and the transitional tillage variant. Accordingly, the content of valuable water-resistant aggregates (3–0.5 mm) was 1.3 times greater due to an increase of 4.9–6.7% and a decrease in the number of aggregates sized 0.5–0.25 mm by 2.8–5.4%. The distribution pattern of water-resistant aggregates within the agronomically valuable range varied with different tillage methods, as indicated by the exponential equations, in which the regression coefficients for the variables significantly differed from each other, as did the values of the constant terms of the exponential equations.

Regardless of the method of chernozem tillage, the soil's structural state deteriorated during the summer period. The content of structural aggregates sized 3–0.5 mm decreased by 4.7% under surface tillage, by 7.5% under transitional tillage, and by 2.6% under plowing. Concurrently, the quantity of structural aggregates larger than 7 mm increased by 4.9%, 9.2%, and 3.2%, respectively, indicating a deterioration of the chernozem's structural state in crop rotation. This trend of deterioration was more pronounced with surface tillage (Fig. 1).

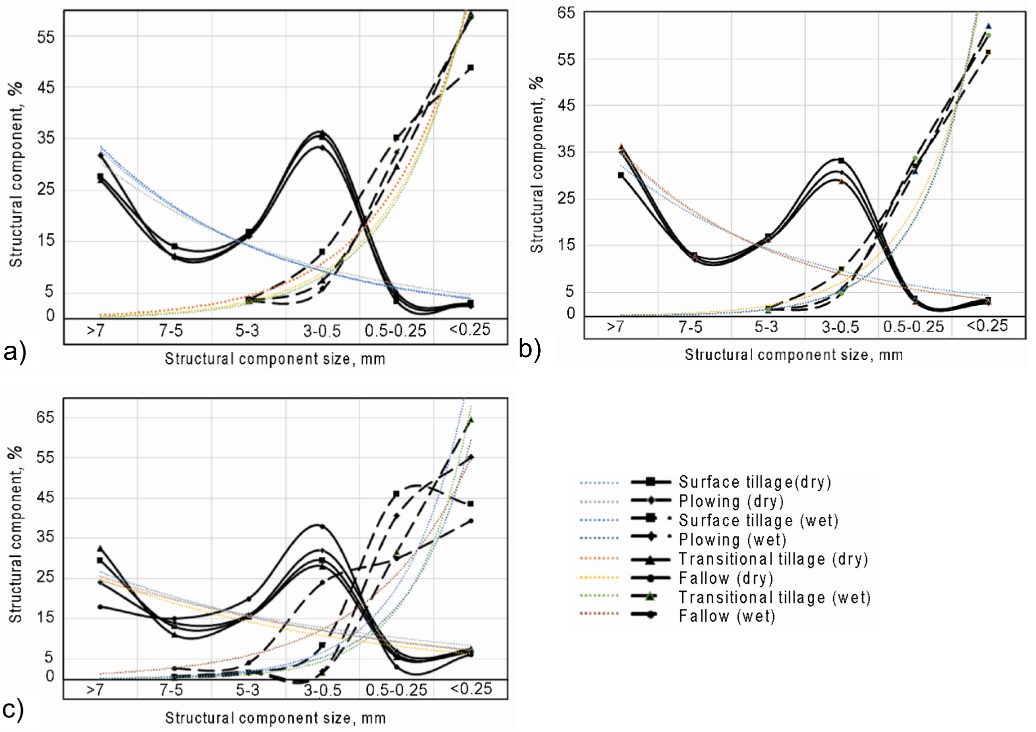

Figure 1. The influence of different tillage systems on the change in the structural-aggregate condition of podzolized chernozem in a 5-field grain crop rotation over the 6th year of their systematic implementation: a – April–May; b – June–July; c – September–October; ······ – approximated data.

In the summer period, surface tillage leads to a deterioration in the water stability of the soil structure, although it remains higher compared to plowing and transitional tillage systems. Specifically, the amount of water-stable aggregates sized 3–0.5 mm under surface tillage was twice as high relative to plowing (4.9%) and 1.7 times higher compared to the transitional system of chernozem tillage. The content of water-stable aggregates sized 0.5–0.25 mm remained similar to the levels observed in the spring period regardless of the tillage method. The amount of water-stable aggregates larger than 0.25 mm increased by 7.6% under surface tillage, while it decreased by 2.5% under transitional tillage and by 2% under plowing, which is close to the amount of water-stable aggregates present in the spring period in the latter two cases (Fig. 1).

It was found that in the autumn period, surface tillage led to a deterioration in the structural condition due to an increase in the content of aggregates larger than 7.0 mm, which were higher by 5.5% compared to plowing and by 8. 5% compared to transitional tillage. Consequently, there was a decrease in the content of the most valuable fraction sized 3–0.5 mm by 7–8% compared to plowing. The total amount of valuable aggregates was highest under surface tillage, while under transitional tillage and plowing, the amount of valuable aggregates was lower by 1.22–1.60 times.

The redistribution of water-resistant aggregates within the agronomically valuable interval was most favorable with surface tillage: the most valuable aggregates (3–0.5 mm) were 6.5% more abundant, or 4.48 times more abundant compared to plowing. At the same time, water-resistant aggregates < 0.25 mm with surface tillage were 1.25 times fewer compared to plowing, and 1.48 times fewer compared to transitional tillage, indicating a significant improvement in water-resistant structure over 6 years of systematic surface tillage in the crop rotation of the 5-field crop rotation. The redistribution of structural fractions and water-resistant aggregates with prolonged fallow indicates a high potential for aggregation of degraded chernozem, and the processes of structural formation during systematic surface tillage are directed towards reproducing structural formation in the fallow, although by the 6th year of the experiment, the realization of possible structural formation is insufficiently manifested (Fig. 1). Similar results were obtained Rieznik et al. (2021).

Based on the analysis using the principal component method (factor analysis) (Table 1), it was found that the first (F_1) and second (F_2) principal components describe the majority of the variation in the characteristics of the structural composition components under consideration - approximately 84%: the F_1 component, which is the most significant, accounts for 55% of the variance, and F_2 accounts for 29%. The F_3 component accounts for the variance of determination errors and is therefore not considered.

Table 1. Factor loading of the components of the structural-aggregate composition of podzolized chernozem

The components of the structural-aggregate composition	Factor loading	
	Factor F_1	Factor F_2
3–0.5 mm (dry), %	0.05	**0.93**
5–0.5 mm (dry), %	–0.32	**0.86**
$A_{(dry)}$ – agronomically valuable soil aggregates, %	**–0.82**	0.53
$A_{(wet)}$ – agronomically valuable soil aggregates, %	**–0.85**	0.00
3–0.5 mm (wet), %	**–0.94**	–0.21
5–0.5 mm (wet), %	**–0.95**	–0.19
K_{str} – structural coefficient	**–0.85**	0.48
C_{ws} – water stability criterion	0.67	0.54
$d_{(dry)}$ – overall MWD of soil aggregates, mm	0.17	**–0.75**
$d_{a(dry)}$ – MWD of soil aggregates 7–0.25 mm, mm	–0.50	–0.60
$d_{(wsa)}$ – overall MWD of water-stable aggregates, mm	**–0.98**	–0.14
$d_{a(wsa)}$ – MWD of water-stable aggregates > 0.25 mm, mm	**–0.95**	–0.04
Dispersion	0.55	0.29

Note: (dry) – dry sieving; (wet) – wet sieving; (wsa) – water-stable aggregates; MWD – mean weight diameter.

The dynamic properties of chernozems (including soil structure) are subject to standardization and normalization (Dehtyarov et al., 2012), as they characterize fertility, resistance, and recovery capacity after anthropogenic impacts. These properties must be considered to establish the possible limits of changes in dynamic properties, as well as the direction and speed of soil processes, which characterize their agroecological functions.

The typification of parameters of the structural-aggregate state of podzolic chernozem by constituent indicators (Table 1) showed that when linked to the main factor (F_1), there was a strong negative correlation $R = –(0.82–0.95)$. Under dry sieving, the average content of agronomically valuable structural aggregates reached 77.1%, with an amplitude range of $\Delta_a = 10.9\%$. The normalized range was $\Delta_{n(50\%)} = 2.7\%$ (at the 50% significance level), and at the 10% significance level, $\Delta_{n(10\%)} = 8.7\%$, with a coefficient of variation of < 5%. The structure coefficient based on the average value reached $K_{str} = 3.44$, and the amplitude and normalized range for K_{str} were $\Delta_a = 2.2$, $\Delta_{n(50\%)} = 0.5$, $\Delta_{n(10\%)} = 0.89$, with a coefficient of variation $P = 18\%$.

Agronomically valuable fractions of soil aggregates (3–0.5 and 5–0.5 mm) had a strong positive correlation with factor F_2 ($R = +0.86–0.93$). On average, their content was 30.8% and 47.0%, with an amplitude and normalized range at 50% and 10% confidence levels of 9.9 and 10.4; 4.9 and 3.5%, and 8.5 and 8.6%, respectively, with a coefficient of variation (P) of 10.6% and 6.5%, which characterizes the change in this parameter as stable.

The mean weighted diameter of structural aggregates had a strong negative correlation with F_2 ($R > –0.70$) and averaged $d = 4.88$ mm, with an amplitude range $\Delta_a = 2.2$ mm, and a normalized range at 50% and 10% significance levels: $\Delta_{n(50\%)} = 0.47$ mm and $\Delta_{n(10\%)} = 0.89$ mm, with a coefficient of variation (P) of less than 10%.

The factor loading of the mean weighted diameter of agronomically valuable aggregates was not significant ($R < 0.70$), hence, its parameters were similar to those of the mean weighted diameter of the overall sieve, but at a lower quantitative level. The factor loading of the components of the water-resistant structure was relatively high with factor F_1 ($R > –0.80$), indicating that the stability of the structural-aggregate state of podzolized chernozem is primarily determined by the water resistance of the structure (Table 2).

The average content of agronomically valuable aggregates was 40.9%, with an amplitude range (Δ_a) of 27.9%, a normalized range of $\Delta_{n(50\%)} = 7.1\%$ and $\Delta_{n(10\%)} = 18.6\%$, and a coefficient of variation of less than 20%. The content of the most valuable fractions of water-resistant aggregates, 3–0.5 mm and 5–0.5 mm, was 7.84% and 8.86%, respectively, with high levels of variation coefficients of 106.5% and 102.2%.

The amplitude range was $\Delta_{a =} 31.4\%$ and $\Delta_a = 31.1\%$, respectively, with normalized ranges of $\Delta_{n(50\%)} = 5.8–6.2\%$ and $\Delta_{n(10\%)}= 9.2–11.0\%$. The average value of the water resistance criterion (C_{ws}) was at the level of 0.28. The amplitude range for C_{ws} was $\Delta_{cws} = 0.24$, with normalized ranges of $\Delta_{n(50\%)} = 0.08\%$ and $\Delta_{n(10\%)} = 0.16\%$, and a coefficient of variation of 23.9%, indicating the instability and low level of C_{ws} regardless of the treatment system.

The value of the mean-weighted diameter of water-stable aggregates overall and within the agronomically valuable range was in the interval of $d = 0.44–0.48$ mm, with an amplitude range of $\Delta_a = 0.46$ and $\Delta_a = 0.30$ mm. The coefficient of variation for the mean-weighted diameter reached 28%, while the mean-weighted diameter within the agronomically valuable range was less than 20%, indicating its high stability.

Table 2. Typification of parameters of the structural-aggregate composition of podzolic chernozem: general model

Structural component parameters	Parameter value		Amplitude range Δ_a = max–min		Normalized range Δ_n: $\Delta_{50\%} = L_{0.75} - L_{0.25}$ $\Delta_{10\%} = L_{0.90} - L_{0.10}$				Coefficient of variation P, %
	mean	median	min	max	$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.90}$	
	Dry sieving, %								
3–0.5 mm	30.8	29.7	26.6	36.5	28.0	32.9	27.2	35.8	10.6
5–0.5 mm	47.0	47.0	41.8	52.2	45.0	48.6	43.5	52.1	6.48
$A_{(dry)}$	77.1	76.9	71.5	82.5	75.0	78.0	72.0	81.0	3.99
K_{str}	3.44	3.35	2.51	4.71	3.05	3.55	2.68	4.41	17.9
$d_{(dry)}$, mm	4.88	4.89	4.14	5.51	4.69	5.16	4.39	5.28	7.89
$d_{a(dry)}$, mm	4.00	4.08	3.48	4.27	3.89	4.17	3.54	4.23	6.35
$d_{(dry)}$: $d_{a(dry)}$	1.22:1	1.20:1	1.19:1	1.29:1	1.21:1	1.24:1	1.24:1	1.25:1	7.12
	Wet sieving, %								
3–0.5 mm	8.86	5.50	2.68	36.8	3.65	9.90	2.70	13.7	102.2
5–0.5 mm	7.80	4.80	2.45	33.8	3.40	9.20	2.50	11.7	106.4
$A_{(wet)}$	40.9	40.2	31.4	59.5	35.6	42.7	31.7	50.3	18.8
C_{ws}	0.28	0.28	0.14	0.38	0.23	0.31	0.21	0.37	23.9
$d_{(wsa)}$, mm	0.44	0.39	0.33	0.79	0.38	0.48	0.34	0.55	28.0
$d_{a(wsa)}$, mm	0.48	0.45	0.38	0.69	0.41	0.54	0.38	0.61	19.8
$d_{(wsa)}$: $d_{a(wsa)}$	0.92:1	0.87:1	0.87:1	1.14:1	0.93:1	0.89:1	0.89:1	0.91:1	23.4

Note: A – agronomically valuable soil aggregates; (dry) – dry sieving; (wet) – wet sieving; (wsa) – water-stable aggregates; MWD – mean weight diameter; K_{str} – structural coefficient; C_{ws} – water stability criterion; d – overall MWD of soil aggregates, mm; d_a – MWD of soil aggregates > 0.25 mm, mm.

Calculations showed that there was a direct correlation between the mean-weighted diameter of water-stable aggregates and the components of the structural-aggregate composition, with $R = +(0.71–0.96) \pm 0.02$. In contrast, the correlation with the water stability criterion was inverse at $R = –(0.67–0.71) \pm 0.02$. A similar inverse relationship was found between the water stability criterion and the content of agronomically valuable water-stable aggregates, as well as the content of the most valuable fractions of water-stable aggregates (3–0.5 mm and 5–0.5 mm), at $R = –(0.65–0.72) \pm 0.03$.

Evaluation of the water stability criterion (C_{ws}) showed that, under plowing and transitional tillage, this indicator averaged $C_{ws} = 0.31–0.33$ over the period of measurements, compared to $C_{ws} = 0.25$ and $C_{ws} = 0.14$ under fallow conditions. This is 1.24–1.32 times lower than under plowing and transitional tillage with surface treatment and 2.21–2.35 times lower under fallow conditions.

It has been established that the improvement of water-stable structure leads to an increase in the size of the mean-weighted water-stable aggregates while reducing the water stability criterion (C_{ws}). This process occurs due to the enlargement of aggregates larger than 1 mm, as observed with surface treatment and fallow conditions. In contrast, plowing and transitional tillage result in the formation of more aggregates smaller than 1 mm.

Based on the established regularity, the C_{ws} index is deemed unreliable for assessing the improvement of water-stable structure, while the mean-weighted diameter of water-stable aggregates serves as a reliable and sensitive evaluative criterion for such enhancement.

Regression equations between the mean-weighted diameter of water-stable aggregates and the C_{ws} index have been determined for the podzolized chernozem:

$Y_{d(wsa)} = 0.44 – 0.38x_1$; $R = –0.70$; $R^2 = 0.49$;

$Y_{da(wsa)} = 0.49 – 0.44x_2$; $R = –0.69$; $R^2 = 0.48$,

where $Y_{d(wsa)}$ – represents the mean-weighted diameter of water-stable aggregates across the entire size range, and $Y_{da(wsa)}$ represents the mean-weighted diameter of water-stable aggregates within the agronomically valuable interval.

For structural components:

$Y_{d(dry)} = 51.5 – 4.25x$; $R = –0.55$; $R^2 = 0.30$, where x represents the content of aggregates sized 3.0–0.5 mm.

The dynamics of the mean-weighted diameter $d_{(dry)}$ of structural components across the entire sieve range and within the agronomically valuable interval $d_{a(dry)}$, along with their ratio, showed that during the period from April to July under surface tillage, the ratio remained constant at 1.24–1.28 to 1, decreasing to 1.18 to 1 in September. During this time, $d_{(dry)}$ ranged from 5.07–5.30 mm, while $d_{a(dry)}$ ranged from 4.01–4.17 mm. In the autumn period, these indicators were 4.17 mm and 3.99 mm, respectively (Table 3).

During the transition tillage, the values of $d_{(dry)}$ in the spring period were at the level of 4.69 mm, with the ratio of $d_{(dry)}$ to $d_{a(dry)}$ being 1.10 to 1. In the summer-autumn period, $d_{(dry)}$ ranged from 4.37 to 5.51 mm. The $d_{a(dry)}$ indicator decreased by autumn from 4.24 mm to 3.89 mm, with the ratio ranging from (1.24–1.30) to 1.

During systematic plowing, the $d_{(dry)}$ indicator in the spring-summer period ranged from 5.02 to 5.28 mm, while in the autumn period, this indicator decreased to 4.14 mm. The $d_{a(dry)}$ indicator throughout the period from spring to summer was lower compared to surface and transitional tillage, indicating lower structuring of the 0–30 cm layer of chernozem. The presence of fallow contributed to $d_{(dry)}$ and $d_{a(dry)}$ approaching a ratio close to 1 to 1, with values of 4.58 mm and 4.27 mm, respectively. This is associated with the insignificant content of clod fraction of structural aggregates > 7 mm.

The dynamics of the weighted mean diameter $d_{(wsa)}$ of water-stable aggregates and $d_{(wsa)}$, as well as their ratio, showed that under surface tillage, this ratio remained stable (0.90–0.95 to 1). During transitional tillage and plowing, this ratio decreased from spring to autumn, but at lower absolute values. When fallow was present, the components of this ratio increased, with the ratio reaching 1.14 to 1.

It was found that during 6 years of systematic surface tillage, the formation of water-stable structure occurred in the direction of retaining fallow, thus mimicking natural soil formation and improving the water resistance of chernozem structure.

The application of fractal theory to soil structure modeling, based on such modeling, as well as to calculations of soil differential porosity and the patterns of physical processes flow in similar dispersed media, is quite promising (Chefetz et al., 2002; Pirmoradian et al., 2005).

Table 3. The dynamics of the mean-weighted diameter of structural aggregates and water-stable aggregates in agrogenic and post-agrogenic tillage of the podzolized chernozem over the 6 years from the beginning of the study

Soil tillage method	Periods of the Year			
	April-May	June	July	September
	Dry sieving			
Surface tillage	5.16*	5.35	5.07	4.71
	4.17	4.17	4.01	3.99
$d_{(dry)}$ to $d_{a(dry)}$	1.24 to 1	1.28 to 1	1.26 to 1	1.18 to 1
Transitional	4.69	5.51	4.73	4.89
	4.23	4.23	3.83	3.89
$d_{(dry)}$ to $d_{a(dry)}$	1.10 to 1	1.30 to 1	1.24 to 1	1.26 to 1
Plowing	5.02	5.28	4.39	4.14
	4.08	4.08	3.54	3.48
$d_{(dry)}$ to $d_{a(dry)}$	1.23 to 1	1.29 to 1	1.24 to 1	1.19 to 1
Fallow	4.58			
	4.27			
$d_{(dry)}$ to $d_{a(dry)}$	1.10 to 1			
	Wet sieving			
Surface tillage	0.55	0.45	0.30	0.45
	0.61	0.50	0.40	0.50
$d_{(wsa)}$ to $d_{a(wsa)}$	0.92 to 1	0.90 to 1	0.95 to 1	0.90 to 1
Transitional	0.49	0.38	0.33	0.34
	0.56	0.43	0.38	0.38
$d_{(wsa)}$ to $d_{a(wsa)}$	0.92 to 1	0.88 to 1	0.87 to 1	0.89 to 1
Plowing	0.48	0.39	0.34	0.38
	0.54	0.44	0.39	0.45
$d_{(wsa)}$ to $d_{a(wsa)}$	0.92 to 1	0.89 to 1	0.87 to 1	0.84 to 1
Fallow	0.79			
	0.69			
$d_{(wsa)}$ to $d_{a(wsa)}$	1.14 to 1			

Note: (dry) – dry sieving; (wsa) – water-stable aggregates; MWD – mean weight diameter; d – overall MWD of soil aggregates, mm; d_a – MWD of soil aggregates > 0.25 mm, mm.

The assessment of the distribution of structural components and stable aggregates showed (Table 4) that under fractal dimensionality (D), surface and combined treatments exhibited a stable distribution of components within the agronomically valuable interval ($D < 1.40$), whereas under systematic plowing, the distribution was unstable ($D > 1.40$). According to the Hurst exponent, the distribution under surface and combined treatments was persistent ($H > 0.5$), whereas under plowing, it tended towards anti-persistent and approached a volatile state. The degree of correlation in the distribution series in the first two cases was at the level of strong inverse correlation, indicating a high level of self-regulation in the structural state of the chernozem (Table 4).

The assessment of redistribution of water-resistant aggregates within the agronomically valuable interval revealed a nonpersistent nature of the aggregate distribution ($D > 1.40$), whereas with plowing, the distribution of aggregates approached a volatile state. The autocorrelation coefficient in the distribution series of aggregates was at a high direct functional level. The presence of a direct functional relationship in the distribution series indicates the instability of the water-resistant structure, which increases from surface tillage to plowing.

Table 4. A comparative fractal assessment of the structural-aggregate state of podzolized chernozem over the vegetation period in a short rotation crop rotation

Soil tillage method	Exponential equation $y = ae^{\pm bx}$	Fractal indicator F_{i}	Fractal dimension $D = 1+\|F_{\mathrm{i}}\|$	Hurst exponent $H = 2 - D$	Correlation relationship $C_H = 2^{2H-1} - 1$
	Dry sieving				
	April–May				
Surface tillage	$y = 49.6e^{-0.42x}$	–0.45	1.45	0.58	+0.15
Transitional*	$y = 43.9e^{-0.37x}$	–0.37	1.37	0.65	+0.20
Plowing	$y = 51.3e^{-0.43x}$	–0.43	1.43	0.57	+0.15
	June–August				
Surface tillage	$y = 33.4e^{-0.25x}$	–0.25	1.25	0.75	+0.45
Transitional	$y = 37.7e^{-0.30x}$	–0.30	1.30	0.70	+0.35
Plowing	$y = 28.7e^{-0.21x}$	–0.21	1.21	0.76	+0.39
	September				
Surface tillage	$y= 34.7e^{-0.26x}$	–0.26	1.26	0.74	+0.40
Transitional	$y= 32.9e^{-0.25x}$	–0.25	1.25	0.75	+0.42
Plowing	$y= 30.4e^{-0.22x}$	–0.22	1.22	0.78	+0.47
Fallow	$y= 32.7e^{-0.27x}$	–0.27	1.27	0.73	+0.38
	Wet sieving				
	April–May				
Surface tillage	$y = 0.31e^{0.81x}$	0.88	1.88	0.12	–0.53
Transitional	$y = 0.18e^{0.98x}$	0.98	1.98	0.02	–0.49
Plowing	$y = 0.14e^{1.03x}$	1.03	2.03	–0.03	–0.45
	June–August				
Surface tillage	$y = 0.037e^{1.26x}$	1.26	2.26	–0.26	–0.52
Transitional	$y = 0.016e^{1.39x}$	1.39	2.39	–0.39	–0.84
Plowing	$y = 0.012e^{1.42x}$	1.42	2.42	–0.42	–0.84
	September				
Surface tillage	$y = 0.049e^{1.23x}$	1.23	2.23	–0.29	–0.47
Transitional	$y = 0.002e^{1.36x}$	1.36	2.36	–0.36	–0.37
Plowing	$y = 0.045e^{1.19x}$	1.19	2.19	–0.19	–0.38
Fallow	$y = 0.63e^{0.745x}$	0.75	1.75	0.25	+0.51

Note: Transitional – transitional soil tillage method.

The comparative seasonal fractal assessment of the distribution of structural components within the agronomic interval depending on the tillage method showed that in the spring period, the fractal dimension, regardless of the distribution of structural components under different tillage methods, fell within the following ranges: for surface tillage and plowing, $H = 1.43–1.45$, while for transitional tillage, $H = 1.37$. According to the conclusions (Pirmoradian et al., 2005), when the fractal dimension falls within the range $1.4 \leq D \leq 1.6$, various forces act on the distribution of components (system state), which to a greater or lesser extent compensate each other, leading the soil system to an equilibrium state. Conversely, with transitional tillage, the fractal dimension falls within the range $D < 1.4$, indicating the influence of one or several forces on the system, which are directed in one direction and destabilize the system.

During the summer period, the fractal dimension falls within the range $1.4 \leq D \leq 1.6$, which determines the stability of the distribution of components regardless of the soil tillage method. However, towards the end of the crop vegetation in July, the fractal dimension of the distribution of components falls below $D < 1.4$, leading the soil system into an unstable state.

The analysis of the Hurst exponent showed that for surface tillage and plowing, $H = 0.57–0.59$, indicating the state of the distribution of structural components corresponding to 'white' noise or chaotic behavior of the series, i.e., the lowest reliability of prediction. For transitional tillage, the Hurst exponent falls within the range $0.6 \leq H < 1$, indicating trend persistence and long-term memory effect. However, during the summer period, the state of the distribution of structural components falls within the range of chaotic behavior of the soil system ($0.5 < H < 0.6$) regardless of the soil tillage method. The value of the Hurst exponent for the distribution of components in July, regardless of the tillage method, reached values $D > 1.6$, indicating the instability of the soil structure, with the soil as a system being 'ready' to transition to a new state.

The calculations of correlation (*P*) in the series of distribution of fractions of structural components showed that the stronger the distribution stability according to the *D* and *H* parameters, the weaker the correlation between the fractions. Thus, during the spring period, the correlation coefficient *P* was at a low level ($P = +0.10–0.20$) both in spring and in the summer period.

When the soil system enters a bifurcation state according to the *D* and *H* parameters, the correlation between the fractions of structural components strengthens. For instance, during surface tillage, the correlation coefficient (*P*) increases to +0.45, while for plowing and transitional tillage, it reaches correlation values of $P = 0.35$ to 0.39.

The fractal assessment of water-stable aggregates distribution within the agronomically valuable range indicated that during surface tillage, the fractal dimension (*D*) exceeded $D > 1.6$, characterizing the soil system as unstable and prone to transition to a new state. Regardless of the tillage method, the correlation coefficient in the distribution series of water-stable aggregates ranged from $P = –0.45$ to –0.53, while the Hurst exponent was close to $H = 0$, indicating the unpredictability of the soil system's behavior.

Jimenez et al. (2011) studied the changes in the fractional composition and physicochemical properties of soil at different depths on lands with a 100-year history of agricultural activity. The article noted a gradual restoration of the soil's fractional composition to a level similar to the surrounding tropical forests around the experimental plot.

Nichols & Toro (2011), in developing the Whole Soil Stability Index (WSSI), identified differences in soil quality due to management practices (e.g., number of tillages, plant cover, and crop rotation), with the highest WSSI values observed for fallow land and the lowest for conventional tillage. This fully correlates with the results of our studies.

Niewczas & Witkowska-Walczak (2005) developed a methodology for analyzing the Aggregate Stability Index (ASI) using three soils and different methods for determining water stability. Their research concluded that it is possible to compare the stability of aggregates from different soils or the stability of aggregates from a specific soil during the studies.

The principles of the formation of agrogenic typical chernozems are most thoroughly described in the study by Nosko (2013). The article analyzed changes in the physicochemical, biological, and agrochemical properties of loamy-clayey typical chernozem after 40 years of plowing and sandy-loam typical chernozem under different intensities of use. It confirmed the important role of mineral and organic fertilizers and the methods of their application in the formation of the humus profile, agrophysical, and agrochemical properties. The main trends in the changes of the studied parameters demonstrate the reliability of the results presented in our article.

Fractal comparative analysis is a sensitive tool for assessing the redistribution of structural disparities and water-resistant aggregates, which remain unchanged during 6 years of surface tillage, transitioning tillage based on surface tillage against the backdrop of systematic plowing, and systematic plowing during the growing season of grain crops in a 5-field crop rotation. It was found that the structural-aggregate state of the 0–30 cm layer of chernozem after 6 years of surface tillage was in a better condition in terms of water resistance of aggregates in the seasonal cycle and provided better conditions for further transition to a no-tillage system in the crop rotation compared to surface tillage performed against the background of systematic plowing.

CONCLUSIONS

Fractal comparative analysis is a sensitive tool for assessing the redistribution of structural disparities and water-resistant aggregates, which remain unchanged during 6 years of surface tillage, transitioning tillage based on surface tillage against the backdrop of systematic plowing, and systematic plowing during the growing season of grain crops in a 5-field crop rotation. It was found that the structural-aggregate state of the 0–30 cm layer of chernozem after 6 years of surface tillage was in a better condition in terms of water resistance of aggregates in the seasonal cycle and provided better conditions for further transition to a no-tillage system in the crop rotation compared to surface tillage performed against the background of systematic plowing.

Based on fractal indicators, the condition of water-resistant structure in spring is assessed as unstable, although with surface tillage, the qualitative and quantitative indicators of water resistance are better compared to plowing. During the summer period, the fractal assessment of the water-resistant structure showed that regardless of the soil tillage method, its condition deteriorated to a greater extent. Thus, the fractal dimension was at $D > 2$ level, indicating an extremely unstable state of the water-resistant structure, but the Hurst exponent was $H \leq 0$, indicating the process of destruction of water-resistant aggregates. The correlation coefficient in the distribution series between aggregate fractions decreased to $P = -(0.12–0.20)$, which is a sign of the separation of water-resistant aggregate fractions and a certain stabilization in their dynamics. The most stable water resistance state is achieved with systematic surface tillage, where the P indicator is 1.7 times smaller compared to plowing.

Based on the conducted research, it can be concluded that the systematic application of surface tillage resulted in a better agrophysical condition of the 0–30 cm layer of chernozem in terms of structural state and water resistance compared to plowing and transitional tillage. Importantly, with surface tillage, the water resistance of the soil structure in the 0–30 cm layer of chernozem was in a better qualitative and quantitative state in a seasonal dimension compared to the condition under systematic plowing and transitional tillage. This should be considered as the conclusion of the transitional period (6 years) towards the implementation of a No-till system under continuous execution within a 5-field crop rotation.

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