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Structural-aggregate condition and utilization of productive water reserve depending on the tillage method of podzolized chernozem in agrocenosis

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Abstract. The work established the features of formation of the structural-aggregate condition and determine the main patterns of the formation of spring productive water reserves and its consumption in a five-field crop rotation when cultivating winter wheat and spring cereal crops using different tillage methods (plowing, systematic surface tillage, No-till systems based on plowing and systematic surface tillage) of podzolized chernozem (black soil) in the conditions of the central part of the Forest-Steppe of Ukraine. Common research methods were applied: field, laboratory, mathematical, and comparative-computational. Analysis of the results showed that during surface treatment, water-resistant aggregates are enlarged into the most valuable fraction, which affects the more rational use of productive water reserves during the growth of crops in crop rotation. Under the No-till system (in years 2–3), there is an accumulation of productive moisture in the soil layer of 0–1 m by 8–12 mm more compared to conventional tillage, and relative to the water reserves in 2022, the water reserve in 2023 increased by +19.0 mm (after conventional tillage) and by +14.0 mm (under surface tillage). Under the no-till system, in June and July, the average productive water reserve for the years 2022–2023 was higher compared to conventional tillage by 5–10 mm and 7–10 mm, respectively, and compared to surface tillage by 10–12 mm and 18–21 mm, respectively. In 2023, the productive water reserve in July under the No-till system exceeded that under conventional tillage by 17 mm, and compared to surface tillage by 31 mm. This improvement in soil structure water resistance in June and July was due to the increase in the content of water-stable aggregates sized 3–0.5 mm.

Key words: conventional tillage, fractal dimension, surface tillage, structural condition, water resistance.

INTRODUCTION

The parameters of the physical structure are among the key rapidly changing properties of chernozem (black soil) in agroecosystems of the Forest-Steppe. When chernozem is plowed, there is a sharp change in its structural condition (Medvediev, 2016). Research conducted in the Forest-Steppe zone has established norms for changes in the physical properties of plowed chernozem and the maximum values of their indicators (Medvediev, 2012; Bulyhin et al., 2014; Medvediev et al., 2014). According to Medvediev (1990), reducing the depth and frequency of tillage or abandoning it altogether, practicing high agricultural culture with the application of organic fertilizers, and leaving crop residues in the field deteriorates the structural condition of chernozem under intensive tillage (plowing), while under minimum soil disturbance, the process of chernozem structure reproduction becomes actively sustainable. The structure of chornozem affects the carbon cycle (An et al., 2008; Jimenez et al., 2011), fertility, and humus regime (Garcia-Oliva et al., 2004) of chernozem in agroecosystems (Six et al., 2004). The fundamental properties of chornozem and the primary processes that determine its functions in agroecosystems depend on the proportion of large and small structural elements and water-resistant aggregates. Chernozems dominated by water-resistant macroaggregates contain more organic matter (Pirmoradian et al., 2005; Nichols & Toro, 2011; Nosko, 2017).

Water stability of soil structural aggregates is an important property from an agronomic perspective, but it does not provide a complete characterization of soil structure quality, as two soils with similar structures can be qualitatively different (Bulgakov et al., 2018; Ivanovs et al., 2020). This difference is determined by the intensity of agricultural use of chernozems, as soil structure water stability decreases with increasing anthropogenic load (Six et al., 2000; Gajic et al., 2006; Tkachenko et al., 2016). The most significant role in forming water-stable aggregates is attributed to mobile organic matter because easily mineralized organic substances (labile humic substances) play a significant role in forming water-stable structure (Chefetz et al., 2002; Zaryshnyak et al., 2016¸ Bulgakov et al., 2017).

The study of water stability in plowed chernozems is of great importance for assessing the resilience of soil structure to intensive agricultural impact, which depends on the cultivated crop, predecessor crop, soil tillage method, humus content, and application of organic and mineral fertilizers. The development and outfitting of modern machinery and tractor units to reduce agro-impact on chernozem soil structure is a relevant issue in contemporary soil-climatic conditions of the Ukrainian Forest-Steppe (Kosolap & Krotinov, 2011; Bulgakov et al., 2020; Bulgakov et al., 2021).

A compelling argument in favor of minimal tillage and No-till systems is the soil conservation effect, which is associated with the presence of a mulch layer on the field surface. This layer protects chornozem soils from strong winds and reduces their deflationary losses during prolonged use of intensive tillage technologies. Preservation of soil structure with the introduction of minimal tillage and No-till has been observed in soils of southern and central England, while the positive impact of No-till on aggregate stability and soil erosion resistance has been documented in France and other

Mediterranean countries (Medvediev, 2010). Implementation of No-till in the state of Mississippi (USA) has led to increased stability of air-dry aggregates, contributing to enhanced soil wind resistance (Rhoton, 2000).

An important characteristic of minimal tillage and No-till systems is their erosion-resistant soil structure and their resistance to deflation (wind erosion) (Baydyuk, 2004). The increase in the structural coefficient in the upper layers of chornozem soil under minimal tillage and No-till is associated with the enrichment of the soil environment with organic residues, along with the presence of microorganisms (fungi, bacteria, algae, etc.). These microorganisms bind elementary soil particles (ESPs) during their life processes, releasing polysaccharides and galacturonic acid polymers into the soil. These substances have an enhanced ability to bind ESPs together (Medvediev, 2008). Macrostructure parameters serve as an integral indicator characterizing erosion resistance, including the content of erosion-resistant aggregates larger than 0.25 mm and the mean weighted diameter of these aggregates (Hirte et al., 2017). The critical velocity of water flow that destroys erosion-resistant aggregates is proportional to the mean weighted diameter of these aggregates (Bardgett et al., 2014). Therefore, erosion resistance under No-till in the 0–0.1 m layer increases due to the formation of a soil environment saturated with surface organic residues and containing a large number of heterotrophic microorganisms. These microorganisms generate various adhesive substances, which participate in the formation of erosion-resistant aggregates, along with the formation of so-called labile humus, which has a high aggregation ability (Thorne, 2003; Medvediev, 2007).

The tillage method (plowing, surface tillage, No-till) of chornozem in crop rotation is one of the most important factors influencing fertility reproduction, growth and development, crop formation of agricultural crops. The improvement of tillage systems for chornozem, the reduction of energy costs, and the enhancement of its soil-protective properties are essential issues (Gassen & Gassen, 2004). Additionally, the adaptability to specific conditions, accumulation of spring water reserves, its preservation and expenditure, as well as the reproduction of agrophysical properties of chornozem, including its structural-aggregate composition, remain relevant tasks in agriculture in the central part of the Ukrainian Forest-Steppe region (Chornyi et al., 2012).

The aim of the research is to identify the peculiarities of forming the structural-aggregate state and to determine the fundamental patterns of spring productive water reserves and its consumption in a 5-field grain crop rotation when cultivating winter wheat and spring cereal crops using different cultivation methods (plowing, systematic surface tillage, No-till system based on plowing, and systematic surface tillage) of podzolized chornozem in the conditions of the central part of the Ukrainian Forest-Steppe region.

MATERIALS AND METHODS

The research was conducted at the experimental station of the Cherkasy Research Station of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine under the conditions of a field stationary experiment established in 2010 (coordinates 49°56'46.1"N 32°07'02.1"E). The soil cover of the field is characterized by strongly differentiated low-humus medium loamy podzolized chornozem on a carbonate loess (Polupan et al., 2005) or Chernic Phaeozems (Hyperhumic, Siltic, Calcaric, Cutanic, Episiltic, Sodic) according to WRB 2022. The humus content in the plowed horizon ranges from 2.58% to 3.08%, gradually decreasing with depth to 0.96% at a depth of one meter. According to the norms of agrophysical indicators developed over the previous 5 years of research, the podzolized chornozem meets the requirements for minimal tillage and special raw material zones for agricultural biologization (Fig. 1).

Figure 1. Location of the experimental site (coordinates 49°56'46.1"N 32°07'02.1"E).

The research is conducted in a field stationary experiment to study the productivity of a 5-field grain-legume crop rotation, which includes: spring barley - peas - winter wheat - soybeans - spring wheat (Hordeum vulgare - Pisum sativum - Triticum aestivum - Glycine max - Triticum aestivum). The structure of the crop rotation is as follows: cereals - 60%, including: winter wheat - 20%; spring cereals - 40%; legumes (peas) - 20%; technical crops (soybeans) - 20%.

The tillage system includes: 1) conventional tillage (plowing); 2) surface tillage for 8 years; 3) No-till alongside long-term conventional tillage and 6-year surface tillage at a depth of 10–12 cm. The fertilization system, in the context of the two cultivation systems, consists of: control (no fertilizers) and $N_{55}P_{55}K_{65}$, $N_{75}P_{65}K_{82}$ per hectare of crop rotation area.

The study investigated the impact of long-term use of different cultivation systems on the agrophysical and agrochemical condition of podzolized chornozem when transitioning to the No-till system with minimum tillage. It also examined the transition from systematic tillage and surface tillage to a specialized grain crop rotation, establishing the influence of transitional soil conditions on the productivity and quality of grain crops in a 5-field crop rotation.

Field stationary experiment layout:

1 – Systematic conventional tillage (plowing) from 10–12 cm to 22–25 cm depending on the crop in crop rotation;

2 – No-till system transitioning to minimal tillage (in 2021) after systematic plowing from 10–12 cm to 22–25 cm;

3 – No-till system of tillage through surface tillage at a depth of 10–12 cm for 6 years;

4 – Surface tillage at a depth of 10–12 cm for 8 years.

Fertilization system: $N_{75}P_{65}K_{82}$ per hectare of crop rotation area.

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. 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 in Savinov's N.I. modification (DSTU 4744:2007) (State Standard of Ukraine, 2008), and soil structure stability was determined by I.M. Baksheev's method.

An important indicator of soil structure is the structural coefficient K_{st} (the ratio between the mass of agronomically valuable aggregates (0.25–10 mm) and the total mass of dust (less than 0.25 mm) and aggregates larger than 10 mm). This coefficient allows for a clearer assessment of the impact of different soil tillage methods.

Aggregate water stability is the ability of soil aggregates to resist the destructive action of water. Soils with high humus content have the greatest aggregate water stability. To determine the water stability of soil aggregates, the sieving method developed by Baksheev I.M. (Medvediev, 2008) was used. The C_{ws} criterion for soil water stability is determined by the following formula:

$$C_{ws} = \frac{A_{wet}}{A_{dry}}, \quad (1)$$

where A_{wet} – aggregates larger than 0.25 mm in wet sieving, %; A_{dry} – aggregates larger than 0.25 mm in dry sieving, %.

More than 600 soil samples were analyzed annually (5 agricultural crops; 4 types of soil treatment; 2 soil layers; 3 months of research; 5 repetitions along the diagonal of the experimental area).

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; Field, 2009).

In recent decades, methods of nonlinear dynamics, particularly fractal analysis, have been widely used for the processing and modeling of time series. The main task of fractal analysis is to determine the fractal dimension F_r and the Hurst exponent H_x of time series. It is known that the Hurst exponent is directly related to the fractal dimension F_r by the formula:

$$H_x = 2 - F_r, \quad (2)$$

where F_r is the measure of the roughness of the series (fractal dimension) and H_x is the Hurst exponent.

Mandelbrot used the Hurst coefficient to calculate the dimension of the probability space D_m as:

$$D_m = 1 / H_x, \quad (3)$$

The correlation ratio in this case is calculated by the following formula:

$$C_H = 2^{(2H-1)} - 1, \quad (4)$$

where C_H is the measure of correlation and H_x is the Hurst coefficient.

Amplitude range Δ_a is the difference between the highest and lowest values in a data set (Δ_a = max-min).

Normalized range is the relative range obtained by dividing the amplitude range by a certain characteristic of the distribution, allowing comparison of ranges across different data sets.

Quantile (L) is one of the numerical characteristics of random variables in mathematical statistics. Quantiles divide the range into certain portions. For example, $L_{0.25}$ means that 25% of the variable's values fall below this value.

RESULTS AND DISCUSSION

Research has shown that in the plow layer (0.22–0.25 m), the humus content ranges from 2.58% to 3.08% (according to the Tyurin method), gradually decreasing with depth to 0.92% at a depth of one meter. The sum of absorbed bases ranges from 25.1 to 27.8 mg-eq per 100 g of soil, hydrolytic acidity ranges from 1.87 to 2.22 mg-eq per 100 g of soil, pH of the salt extract ranges from 5.49 to 6.27 - soil to water ratio 1:2.5 (FAO, 2021). The base saturation degree is between 92.7% and 93.5%, the content of exchangeable phosphorus forms (according to the Truog method) is 9.5 mg per 100 g of soil, and exchangeable potassium (according to the Brovkin method) is 11.5 mg per 100 g of soil. The soil at the experimental site has the following morphological profile structure:

$H_{0–4}$ – sod, penetrated by plant roots;

$He_{5–47}$ – 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;

$Hpi_{48–82}$ – 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;

$Ph_{83–123}$ – 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;

$P(h)k_{123–190}$ – loess, 7.5 YR 6/4, earthworm channels, infilled large burrows, layers of carbonates, carbonates in mold form.

The distribution of structural components by size in the 0–0.3 m layer during dry sieving (Fig. 2) under different soil tillage methods is described by exponential equations. It has been determined that in the 0–0.2 m layer in April, with conventional tillage and surface tillage, the fractal dimension (F_r) was F_r = 1.40–1.42, while with the No-till system, F_r = 1.51–1.59, which is persistent in the first case and anti-persistent in the second (Table 1).

In the case of conventional tillage and surface tillage, the correlation between the fractal dimensions of structural components was at a low level (C_H = 0.12–0.15), while in No-till it was at a high level (C_H = 0.95–0.98), indicating the absence of soil's ability to maintain its structural integrity and stability over time in the first case and the presence of this ability in the second case. This is also supported by the degree of ruggedness of the components' redistribution series (D_m), which is ≥ 2.0 in the No-till system, whereas in conventional tillage and surface tillage, D_m is < 2.0.

In June, in the 0–0.2 m layer, the observed pattern of fractal assessment of structural components redistribution persisted. In surface tillage, the correlation value (C_H) doubled (C_H = 0.30), while in conventional tillage, it remained at the April level. The constancy of the fractal assessment of structural components distribution in the No-till system indicates the stability of the soil's structural condition.

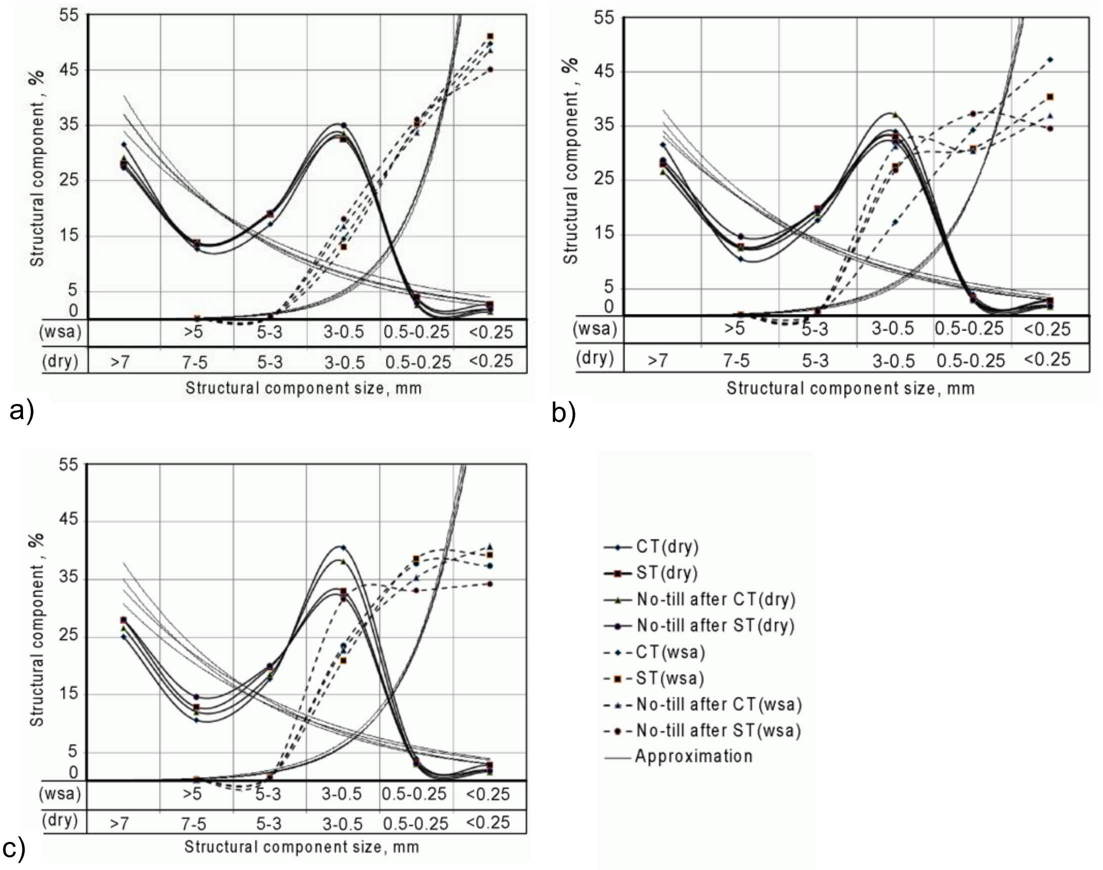


Figure 2. The influence of different tillage systems on the redistribution of structural components and water-stable aggregates in a five-field crop rotation on podzolized chornozem in the third year of implementation in the 0–0.3 m layer: a – April; b – June; c – July; (dry) – dry sieving; (wsa) – water-stable aggregates; (CT) – conventional tillage; (ST) – surface tillage.

In the 0.2–0.3 m layer in April, F_r was consistently above 1.4 regardless of the tillage method, indicating soil system disturbance. The D_m index was consistently above 2.0, and C_H ranged from 0.78 to 0.94, indicating dynamic redistribution of structural components by size. Plowing resulted in a more unstable structure with $F_r > 1.6$. In June, Fr was 1.46 under plowing, while under surface tillage and No-till systems, F_r approached 1.6. Furthermore, D_m was less than 2.0 under plowing but greater than 2.0 under surface tillage and No-till systems, leading to higher C_H values ranging from 0.86 to 0.98.

In July, the established pattern of fractal assessment of structural condition persisted: under surface tillage and No-till systems, the redistribution of components was persistent, while under plowing, it was anti-persistent. This means that in the former case, the soil system exhibited ability to maintain its structural integrity and stability over time, long-term memory, while in the latter case, it was unstable in terms of reproducing soil structure, characterized by redistribution of structural components by size during the spring-summer period.

Table 1. The influence of different tillage methods on the seasonal dynamics of fractal assessment of soil structure condition in the 0–0.3 m soil layer in the five-field crop rotation in the third year of the study

No.	Exponential equation, $Y = ae^{\pm bx}$	Fractal dimension, $Fr = 1+\lvert bx \rvert$	Hurst exponent, $H_x = -F$	Mandelbrot dimension, $Dm = 1: H_x$	Correlation relationship, $C_H = 2^{2H-1} - 1$
	April				
1	$Y = 60.6e^{-0.49x}$	1.49	0.51	1.96	+0.01
2	$Y = 51.89e^{-0.43x}$	1.43	0.57	1.76	+0.10
3	$Y = 60.8e^{-0.50x}$	1.50	0.49	2.00	+0.98
4	$Y = 70.55e^{-0.56x}$	1.56	0.44	2.25	+0.88
	June				
1	$Y = 54.1e^{-0.46x}$	1.46	0.54	1.85	+0.06
2	$Y = 50.7e^{-0.42x}$	1.42	0.58	1.72	+0.12
3	$Y = 62.9e^{-0.51x}$	1.51	0.51	2.00	+0.98
4	$Y = 58.7e^{-0.52x}$	1.51	0.48	2.00	+0.96
	July				
1	$Y = 46.9e^{-0.42x}$	1.42	0.58	1.72	+0.12
2	$Y = 50.7e^{-0.42x}$	1.42	0.58	1.74	+0.12
3	$Y = 62.6e^{-0.51x}$	1.51	0.40	2.00	+0.96
4	$Y = 57.3e^{-0.49x}$	1.49	0.51	1.96	+0.98

Note: 1. Conventional tillage (CT); 2. Surface tillage (ST); 3. No-till after CT; 4. No-till after ST.

The assessment of the structural organization based on the redistribution of structural components in the 0–0.3 m layer showed that in April, F_r under plowing, surface tillage, and No-till systems ranged from $F_r = 1.43$ to 1.56. D_m under plowing and surface tillage was < 2.0, while under the No-till system, D_m was > 2.0, influencing C_H, which ranged from $C_H = 0.06$ to 0.12 under surface tillage and plowing, while under the No-till system, $C_H = 0.98$. In July, the established pattern persisted, indicating higher dynamics in the formation of structural condition during dry sieving in the spring-summer period (Table 2).

In Table 2, the typification of components of the structural condition during dry sieving under different tillage methods for the spring-summer period is presented. Under plowing, the coefficient of variation of the content of dry aggregates sized 7–0.25 mm was 11%, under surface tillage 7.9%, and under the No-till system 9.1%, with average content in the 0–0.3 m layer of chornozem soil ranging from 69.9% to 71.5%. The normalized range varied from 4.4% to 2.0% under plowing and the No-till system, respectively. The coefficient of variation of the content of structural components sized 3–0.5 mm was 13.5% under plowing, 2.03% under surface tillage, and 7.65% under the No-till system, with average contents of 38%, 32.8%, and 34.8%, respectively. The normalized range of the mentioned fractions content was 6.5%, 0.8%, and 5.7%, respectively.

The coefficient of variation of the content of aggregates sized 1–0.25 mm was 31.9% under plowing, 24.8% under surface tillage, and 22.9% under the No-till system, with average contents ranging from 9.6% to 12.9%. Similarly, the coefficient of variation of the content of coarse aggregates (> 7–0.25 mm) was 11.9% under plowing, 5.7% under surface tillage, and 5.7% under the No-till system, with average contents ranging from 27.9% to 32.3%.

Table 2. Normalization of soil structural component parameters depending on the tillage method of the podzolized chornozem (soil layer 0–0.3 m) in a five-field crop rotation during the growing season of spring cereal crops and winter crops

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	$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.90}$	
	Conventional tillage (plowing)								
7–0.25 mm	71.5	72.9	66.8	75.8	69.2	73.6	66.8	75.8	4.32
7–5 mm	11.3	11.6	9.60	13.4	10.6	12.0	9.60	13.4	11.6
5–3 mm	17.6	17.4	16.8	18.8	17.0	17.8	16.8	18.8	4.40
3–0.5 mm	38.0	35.8	32.0	45.2	34.0	40.5	32.0	45.2	13.3
1–0.25 mm	12.9	12.4	8.00	21.5	10.8	13.5	8.00	21.5	31.9
*Non-valuable	27.8	26.8	24.2	33.2	26.0	30.8	24.2	33.2	11.9
K_{st}	2.63	2.77	2.01	3.32	2.25	2.88	2.01	3.32	16.4
***d*, mm	4.31	4.18	3.50	5.30	3.89	4.81	3.50	5.30	14.7
	Surface tillage								
7–0.25 mm	67.9	69.0	64.3	69.8	66.8	69.1	64.3	69.8	2.83
7–5 mm	13.2	13.4	11.6	14.2	12.9	14.2	11.6	14.2	7.90
5–3 mm	19.5	19.8	18.2	21.0	18.6	19.8	18.2	21.0	5.22
3–0.5 mm	32.8	33.0	32.0	33.8	32.2	33.0	32.0	33.8	2.03
1–0.25 mm	10.4	9.60	8.10	16.3	9.00	10.4	8.10	16.3	24.8
Non-valuable	32.3	31.6	30.8	35.8	30.9	33.3	30.8	35.8	5.69
K_{st}	2.25	2.24	1.84	2.49	2.23	2.44	1.84	2.49	9.37
d, mm	4.68	4.64	4.29	4.97	4.55	4.91	4.29	4.97	5.13
	No-till								
7–0.25 mm	70.4	70.2	67.5	74.5	69.4	71.4	68.0	72.0	2.32
7–5 mm	13.5	13.7	11.4	15.4	12.8	14.4	11.4	15.4	9.05
5–3 mm	19.3	19.3	18.2	20.6	18.5	20.1	18.2	20.6	4.48
3–0.5 mm	34.8	33.8	31.8	38.4	32.1	37.8	31.8	38.4	7.65
1–0.25 mm	9.63	8.80	6.80	13.8	8.00	10.8	7.40	13.4	22.9
Non-valuable	29.5	29.6	25.5	32.5	28.3	30.1	27.5	32.0	5.69
K_{st}	2.52	2.44	2.10	3.63	2.32	2.66	2.13	2.86	13.9
d, mm	4.64	4.69	4.10	5.12	4.28	5.02	4.15	5.12	7.96

Note: * Non-valuable – agronomically non-valuable soil particles; ***d* – mean weighted diameter of soil structural aggregates; K_{st} – soil structure coefficient.

The soil structure coefficient, regardless of the tillage method, ranged from K_{st} = 2.25 to 2.63. However, the coefficient of variation was 16.4% under plowing, 9.4% under surface tillage, and 13.4% under the No-till system.

The coefficient of variation for the mean weighted diameter of structural components was 14.7% under plowing, 5.1% under surface tillage, and 7.9% under the No-till system, with average values of 4.31 mm, 4.68 mm, and 4.64 mm, respectively.

The median value under plowing was lower than the mean value, while under surface tillage and the No-till system, it exceeded the mean value and, to a greater extent, approached the upper typical value of the size of structural components. The normalized range of the mean weighted diameter of structural components was 0.92 mm under plowing, 0.36 mm under surface tillage, and 0.44 mm under the No-till system.

Practically, with almost identical levels of structural components in the soil layer 0–0.3 m under different tillage systems, the coefficient of variation of the main components of the structural state during dry sieving is 1.3–6.7 times higher under conventional tillage compared to surface tillage and the No-till system.

In the spring period, in the soil layer 0–0.2 m under conventional tillage, the amount of water-resistant aggregates < 0.25 mm was at the level of 48%, in the soil layer 0.2–0.3 m – 47.4%, and in the layer 0–0.3 m – 47.7%. Under surface tillage, it was 40.0%, 47.9%, and 44.0% respectively. With the No-till system under conventional tillage, the content of water-resistant aggregates < 0.25 mm was at 42.5%, 51.7%, and 45.1%, while with surface No-till tillage, it was 40.9% (0–0.2 m), 45.1% (0.2–0.3 m), and 43% (0–0.3 m). On average, in the soil layer 0–0.3 m, the amount of water-resistant aggregates > 0.25 mm was 52.3% under conventional tillage, which was 5.7% higher compared to surface tillage, 2.7% higher compared to No-till under conventional tillage, and 4.7% higher compared to No-till under surface tillage. The amount of aggregates sized 0.5–0.25 mm in the soil layer 0–0.2 m was the same regardless of the tillage method, ranging from 35.6% to 37.1%. In the soil layer 0.2–0.3 m, under conventional tillage and No-till systems, the amount of aggregates 0.5–0.25 mm was the same (31.8–32.6%), while under surface tillage, it reached 36% (see Table 3).

Table 3. The impact of tillage methods on the water stability of the soil structure in the 0–0.3 m layer of podzolized chornozem in a five-field grain crop rotation in the third year of implementation during the growing season of spring and winter cereals

Tillage method	Size of water-stable aggregates, mm							* C_{ws}	**d, mm
	> 3	3–0.5	1–0.5	0.5–0.25	< 0.25	0.5–0.25 to 1–0.5	> 0.25		
	April								
Conventional tillage (CT)	0.87	12.8	12.8	34.9	49.7	2.7	49.3	0.21	0.43
Surface tillage (ST)	0.60	13.4	13.4	37.9	46.4	2.8	49.2	0.22	0.41
No-till after CT	0.88	14.9	14.9	33.7	48.6	2.3	54.2	0.15	0.44
No-till after ST	0.73	16.7	16.7	36.1	45.0	2.2	56.1	0.16	0.44
Fallow	4.49	16.5	16.5	28.4	41.0	1.7	59.0	0.12	0.53
	June								
CT	0.95	14.0	14.0	34.3	47.2	2.46	52.8	0.23	0.46
ST	1.04	24.3	24.3	30.9	40.5	1.27	59.5	0.15	0.51
No-till after CT	1.26	27.1	27.1	30.4	34.6	1.12	65.4	0.13	0.54
No-till after ST	1.25	22.8	22.8	37.3	37.0	1.64	63.0	0.17	0.55
	July								
CT	1.44	19.5	19.5	37.7	37.3	1.93	62.7	0.19	0.49
ST	1.12	17.3	17.3	38.7	39.2	2.23	60.8	0.14	0.51
No-till after CT	1.16	18.4	18.4	35.3	40.8	1.92	59.2	0.19	0.52
No-till after ST	1.14	27.3	27.3	33.0	34.3	1.21	65.7	0.13	0.57

Note: *C_{ws} – water stability criterion; **d – mean weighted diameter of soil structural aggregates.

On average, in the 0–0.3 m soil layer, the content of water-stable aggregates sized 0.5–0.25 mm ranged from 34.2% to 35.8%. Valuable aggregates sized 3–0.5 mm in the 0–0.2 m soil layer were higher with surface tillage and No-till compared to plowing by 10% and 20.1–21.6%, respectively. Conversely, in the 0.2–0.3 m layer, plowing had more aggregates of this size by 3.3–3.8% compared to other cultivation methods.

In the 0–0.3 m soil layer, the average proportion of aggregates sized 3–0.5 mm was lowest with plowing (16.6%), while with surface tillage and No-till, it increased to 21.7% and 19.4–19.8%, respectively. In June (during the heading phase of spring and winter cereals), the distribution of water-stable aggregates slightly changed. The quantity of water-stable aggregates < 0.25 mm with plowing was higher compared to surface tillage by 5.5% (0–0.2 m), 8.2% (0.2–0.3 m), and by 4.5% (0–0.3 m). With No-till, the quantity of aggregates <0.25 mm was lower compared to plowing by 8.3–8.7% (0–0.2 m), 13–17% (0.2–0.3 m), and by 8.3–10.7% (0–0.3 m).

The highest quantity of water-stable aggregates sized 0.5–0.25 mm was observed with plowing and No-till using surface tillage, reaching 35.2–36.3% (0–0.2 m). Conversely, with surface tillage and No-till using plowing, the quantity of aggregates was lowest, being 8.8% less. In the soil layer 0.2–0.3 m, the content of aggregates sized 0.5–0.25 mm ranged from 31.4–33.2%, while in the 0–0.3 m layer, it ranged from 30.3–30.9% with surface tillage and No-till. However, with plowing, the content reached 34.3%.

The least amount of water-stable aggregates in the most valuable fraction (3–0.5 mm) was observed with plowing: 18.4% (0–0.2 m), 16.6% (0.2–0.3 m), and 19.5% (0–0.3 m). With surface tillage, there was an increase in the content of aggregates sized 3–0.5 mm compared to plowing by 12% (0–0.2 m), 7.2% (0.2–0.3 m), and 8.1% (0–0.3 m). Under the No-till system, the increase ranged from 9.4–14.7% (0–0.2 m), 11.0–13.7% (0.2–0.3 m), and 11.8–14.8% (0–0.3 m). This indicates an aggregation of water-stable aggregates into the most valuable fraction of water-stable aggregates.

During the ripening stage (July) of winter and spring cereals, the content of water-stable aggregates < 0.25 mm in the 0–0.2 m soil layer under plowing was 35.9%, while under surface tillage and the No-till system, their quantity increased by 5.1% and 6.8–7.2%, respectively. In the 0.2–0.3 m soil layer, the highest amount of non-valuable aggregates was observed under the No-till system with plowing, while in other variants, their quantity ranged from 35.4–38.8%. In the 0–0.3 m soil layer, the content of non-valuable aggregates ranged from 37.3–40.8%.

In July, there were more water-stable aggregates of 0.5–0.25 mm under plowing and surface tillage, while under the No-till system, the quantity of aggregates of this size was 4.5–5.0% lower. The highest amount of valuable water-stable aggregates (3–0.5 mm) was consistent across all tillage methods. Regarding the distribution of water-stable aggregates, a return to the distribution observed in April was noted, but the level of water stability of structure was higher under plowing, whereas under surface tillage and the No-till system, the water stability of the structure deteriorated slightly compared to its condition in June.

The normalization of parameters of water-stable structure in seasonal measurements revealed a significant influence of tillage methods on its condition. For instance, the average content of water-stable aggregates sized 3–0.5 mm was 19.5% under plowing, 21% under surface tillage, and 24.4% under the No-till system, which is 1.25 times higher (Table 4). The normalized range under plowing was Δ_n = 8.5%, while at No-till system, it was Δ_n = 11.8%, with higher values of interval limits by 1.06–1.6 times compared to plowing in the latter case.

Table 4. Normalization of parameters of water-stable structure components depending on the tillage method of podzolized chornozem (soil layer 0–0.3 m) in a five-field grain crop rotation during the growing season of spring and winter cereal crops

Structural component parameters	The content of water-stable aggregates		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	$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.90}$	
	Conventional tillage								
> 3 mm	1.11	1.05	0.64	1.96	0.92	1.08	0.64	1.96	34.7
3–0.5 mm	19.5	18.5	10.3	28.3	17.5	18.9	10.3	28.3	28.8
1–0.5 mm (a)	14.3	14.0	9.30	19.5	12.9	15.3	9.30	19.5	19.5
0.5–0.25 (b)	35.5	34.9	32.4	40.2	33.9	37.1	32.4	40.2	7.22
< 0.25 mm	44.9	47.2	35.9	52.0	40.0	49.7	35.9	52.0	13.1
b/a	2.57	2.47	1.95	4.00	2.41	2.63	1.95	4.00	23.2
> 0.25 mm	54.8	52.8	48.0	64.1	49.9	60.0	48.0	64.1	11.2
C_{ws}	0.21	0.22	0.17	0.24	0.19	0.23	0.17	0.24	13.0
d, mm	0.46	0.46	0.39	0.51	0.45	0.48	0.39	0.51	7.61
	Surface tillage								
> 3 mm	0.92	1.00	0.20	1.44	0.80	1.10	0.20	1.44	38.5
3–0.5 mm	20.9	21.2	13.2	30.5	15.3	23.8	13.2	30.5	27.7
1–0.5 mm (a)	17.8	17.3	9.40	26.8	13.4	21.0	9.40	26.8	31.1
0.5–0.25 (b)	35.3	36.0	29.5	41.0	33.2	37.9	29.5	41.0	10.5
< 0.25 mm	43.1	41.0	37.4	54.2	39.2	46.4	37.4	54.2	12.6
b/a	2.17	2.24	1.11	3.68	1.27	2.69	1.11	3.68	39.0
> 0.25 mm	56.5	59.0	46.3	62.6	52.1	60.8	46.3	62.6	10.3
C_{ws}	0.17	0.17	0.11	0.24	0.14	0.19	0.11	0.24	25.9
d, mm	0.47	0.49	0.38	0.53	0.44	0.51	0.38	0.53	11.1
	No-till								
> 3 mm	1.07	1.10	0.70	1.40	0.88	1.26	0.73	1.40	21.9
3–0.5 mm	24.4	26.6	13.1	34.8	18.5	30.3	14.6	31.6	27.3
1–0.5 mm (a)	21.3	22.9	12.9	29.7	16.6	26.0	13.2	28.9	26.6
0.5–0.25 (b)	34.3	34.5	29.5	39.8	31.8	36.1	30.4	39.5	8.83
< 0.25 mm	39.9	38.0	33.0	51.7	35.4	45.0	33.1	48.6	14.3
b/a	1.55	1.43	0.89	2.73	1.04	2.02	0.97	2.72	36.9
> 0.25 mm	60.7	62.0	54.0	67.0	56.1	64.6	54.2	66.9	7.78
C_{ws}	0.15	0.16	0.12	0.21	0.13	0.17	0.12	0.19	16.7
d, mm	0.51	0.52	0.42	0.58	0.44	0.55	0.44	0.57	10.6

Note: *C_{ws} – water stability criterion; **d – mean weighted diameter of soil structural aggregates.

The content of water-stable aggregates sized 3–0.5 mm, by the median, was lower than the mean under plowing, whereas under surface tillage and the No-till system, it was higher than the mean, indicating a tendency of the content of this fraction towards the upper typical value. The coefficient of variation of the content of the 3–0.5 mm fraction of water-stable aggregates was 28.8% under plowing and 27.3–27.6% under surface tillage and the No-till system, which is practically the same. The content of the 1–0.5 mm fraction of water-stable aggregates was 14.3% under plowing, 17.8% under surface tillage, and 21.3% under the No-till system, which is 1.5 times higher. The normalized range of the content of this fraction of water-stable aggregates was Δ_n = 2.4% under plowing, Δ_n = 7.6% under surface tillage, and Δ_n = 9.4% under the No-till system, with significantly higher (1.4–1.7 times) values of interval limits.

The coefficient of variation of the content of water-stable aggregates sized 1–0.5 mm was 19.5% under plowing, while under surface tillage and the No-till system, it increased to 26.6–31.1%, which is 1.36–1.6 times higher.

The average content of water-stable aggregates sized 0.5–0.25 mm, regardless of the tillage method, ranged from 34.3% to 35.5%. However, the median content of this fraction was lower than the average content under plowing, whereas under surface tillage and the No-till system, the median content exceeded the average. This indicates an increase in their content due to a decrease in the content of water-stable aggregates smaller than 0.25 mm. The coefficient of variation increased from plowing (7.22%) to surface tillage and the No-till system (8.8–10.5%).

The average ratio of water-stable aggregates sized 0.5–0.25 mm to 1.05 mm was 2.57 to 1 under plowing, 2.17 to 1 under surface tillage, and 1.55 to 1 under the No-till system, with an amplitude range of Δ_a=2.05 units (plowing), Δ_a = 2.57 units (surface tillage), and Δ_a = 1.84 units (No-till). The normalized range was Δ_n = 0.22 (plowing), Δ_n = 1.42 (surface tillage), Δ_n = 0.98 (No-till), with lower values in the range of 1.3–2.32 interval values of the normalized interval.

The coefficient of variation (*P*) for ratio under plowing was at 23.2%, while under surface tillage and the No-till system, variability increased by 1.58–1.68 times, indicating an active process of rearrangement of water-stable aggregates from the 0.5–0.25 mm fraction to the 1–0.5 mm fraction.

The average content of water-stable aggregates larger than 0.25 mm under plowing was 54.8%, under surface tillage - 56.5%, and under the No-till system - 60.7%, which was higher compared to plowing by 5.9%. The content of this fraction of water-stable aggregates at the median under plowing was lower than the mean by 2%, while under surface tillage and the No-till system, it was higher by 2.5% and 1.3% respectively, indicating a tendency for the content of agronomically valuable aggregates under plowing to gravitate towards the lower typical value, while under surface tillage and the No-till system, it tends towards the upper typical value, leading to a decrease in the content of this fraction larger than 0.25 mm under plowing and an increase under surface tillage and the No-till system.

The coefficient of variation in the content of water-stable aggregates larger than 0.25 mm under plowing and surface tillage was 10.3–11.2%, while under the No-till system, it was 7.78%. Conversely, the content of water-stable aggregates smaller than 0.25 mm changed. The average content under plowing was 44.9%, while under the No-till system, it was 39.9%, which is 5% less. At the median, the content of non-valuable aggregates was higher than the mean under plowing, while under surface tillage and the No-till system, it was lower than the mean, indicating an increase in the former case and a decrease in the latter.

The mean value of the water stability index (C_{ws}) under plowing was $C_{ws} = 0.21$, under surface tillage $C_{ws} = 0.17$, and under the No-till system $C_{ws} = 0.15$. The median value of C_{ws} exceeded the mean under plowing, while under surface tillage and the No-till system, it remained at the mean level.

The normalized range of C_{ws} under plowing ranges from 0.04 to 0.07 units, under surface tillage from 0.05 to 0.13 units, and under the No-till system from 0.04 to 0.07 units. However, the interval values of the normalized ranges are lower.

The coefficient of variation under plowing was 13%, while under surface tillage it doubled, and under the No-till system, it increased by 1.29 times.

The decrease in the value of C_{ws} during surface tillage is associated with the aggregation of water-stable aggregates and their accumulation in fractions larger than 1 mm, which is linked to the increase in the fraction of 3–0.5 mm and the decrease in the ratio of fractions 0.5–0.25 mm to 1–0.5 mm, as shown above.

The average value of the mean weighted diameter of water-stable aggregates (d, mm) during conventional tillage was $d = 0.46$ mm, during surface tillage $d = 0.47$ mm, and during No-till $d = 0.51$ mm, which is 1.11 times higher.

The normalized indicators of the mean weighted diameter of water-stable aggregates were: 0.03–0.17 mm (CT), 0.07–0.15 mm (ST), and 0.11–0.13 mm (No-till), with higher values of the extreme interval values of the diameter size of water-stable aggregates. These values were 1.12–1.15 times higher in No-till compared to conventional tillage, with a coefficient of variation of 10.6–11.1% for surface tillage and No-till, and 7.61% for conventional tillage.

Calculations show that at conventional tillage, there were 11 significant correlation relationships ($R > \pm 0.7$) between indicators of soil structural condition and components of structural stability, comprising 9 pairs of strong positive correlations and 2 pairs of negative correlations. These correlations represent 11%, 9%, and 2% of the total number of pairwise correlations in the matrix field. Pairwise correlation coefficient calculations between components of soil structural condition revealed that in conventional tillage, there were 27 significant strong positive correlations (49%), 14 pairs of positive correlations (25.5%), and 13 pairs of negative correlations (23.6%). In surface tillage and No-till, there were 24 significant correlations (43.6%), 11 pairs of positive correlations (20%), and 13 pairs of negative correlations (23.7%). This indicates a nearly uniform soil structural condition in the 0–0.3 m layer of chornozem regardless of the tillage method.

In surface tillage, there were a total of 28 pairwise correlations (28%), with 12 positive correlations (12%) and 16 mutual correlations (16%). In the No-till system, there were 16 correlations (16%), comprising 9 positive correlations (9%) and 7 mutual correlations (7%) (Table 5).

The assessment of the water-resistant structure condition through paired correlations depending on the tillage method showed that with plowing, there were 15 significant correlation links ($R > \pm 0.7$) (42%), comprising 8 direct links (22%) and 7 inverse links (19%). With surface tillage, there were 21 links (58%), with 11 direct (31%) and 10 inverse (27.8%). In the No-till system, there were 23 links (63%), with 12 direct (33.3%) and 11 inverse (30.6%), respectively.

Table 5. The influence of different tillage methods on the coefficients of pairwise correlations between the parameters of the structural-aggregate state in the five-field grain crop rotation

	d, mm (dry)*	> 3 mm	3–0.5 mm	1–0.5 mm	0.5–0.25 mm	< 0.25 mm	X_5 to X_4	> 0.25 mm	C_{ws}	*d*, mm (wsa)**
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}
	No-till									
X_1	1.00	–0.81	–0.64	–0.54	0.25	0.65	0.63	–0.71	–0.15	–0.71
X_2		1.00	0.62	0.52	–0.28	–0.63	–0.61	0.66	0.21	0.82
X_3			1.00	0.95	–0.46	–0.90	–0.96	0.95	–0.33	0.89
X_4				1.00	–0.54	–0.87	–0.89	0.92	–0.51	0.83
X_5					1.00	0.12	0.57	–0.34	0.43	–0.24
X_6						1.00	0.77	–0.94	0.27	–0.92
X_7							1.00	–0.85	0.23	–0.82
X_8								1.00	–0.39	0.91
X_9									1.00	–0.11
X_{10}										1.00
	Surface tillage									
X_1	1.00	–0.65	–0.82	–0.74	0.32	0.75	0.64	–0.79	0.41	–0.88
X_2		1.00	0.60	0.56	–0.14	–0.72	–0.66	0.73	–0.52	0.87
X_3			1.00	0.98	–0.60	–0.77	–0.94	0.80	–0.60	0.86
X_4				1.00	–0.59	–0.77	–0.96	0.78	–0.63	0.82
X_5					1.00	–0.03	0.54	–0.04	–0.11	–0.23
X_6						1.00	0.78	–0.97	0.84	–0.91
X_7							1.00	–0.78	0.70	–0.82
X_8								1.00	–0.87	0.94
X_9									1.00	–0.71
X_{10}										1.00
	Conventional tillage (plowing)									
X_1	1.00	–0.35	–0.25	–0.13	–0.00	0.35	0.21	–0.42	–0.53	–0.47
X_2		1.00	0.90	0.44	–0.22	–0.80	–0.53	0.78	–0.11	0.82
X_3			1.00	0.71	–0.02	–0.87	–0.70	0.84	–0.32	0.86
X_4				1.00	0.17	–0.65	–0.88	0.61	–0.61	0.72
X_5					1.00	–0.36	0.26	0.40	–0.20	0.03
X_6						1.00	0.51	–0.99	0.35	–0.90
X_7							1.00	–0.46	0.51	–0.77
X_8								1.00	–0.28	0.88
X_9									1.00	–0.37
X_{10}										1.00

Note: *(dry) – dry sieving; ** (wsa) – water-stable aggregates; C_{ws} – water stability criterion; *d* – mean weighted diameter of soil structural aggregates.

In analyzing the components of the structural-aggregate state of chornozem using 17 quantitative variables, it was found that regardless of the tillage method, 3 factors were identified, accounting for: F_1 – 50–52%, F_2 – 22–25%, and F_3 – 11–17% of the total variance, totaling 74–75% of the variance across F_1–F_2. In terms of tillage systems: 86% – plowing, 91% – surface tillage, 80% – No-till system (Table 6).

Table 6. Factor loading of the components of the structural-aggregate composition depending on the tillage method of podzolized chornozem in a five-field crop rotation

	Conventional tillage (plowing)			Surface tillage			No-till		
	F_1	F_2	F_3	F_1	F_2	F_3	F_1	F_2	F_3
	Dry sieving								
7–0.25 mm	0.91	–0.37	–0.04	–0.66	–0.71	0.17	0.64	0.67	0.17
7–5 mm	–0.91	0.32	0.22	–0.61	0.30	–0.71	–0.09	–0.36	0.85
5–3 mm	–0.07	0.30	–0.33	0.24	–0.05	–0.93	–0.17	–0.47	0.75
3–0.5 mm	0.93	–0.26	–0.07	0.59	–0.32	0.66	0.21	0.46	–0.79
1–0.25 mm	0.49	–0.62	–0.33	0.53	0.31	0.56	0.75	0.30	–0.41
Non-valuable	–0.83	0.06	0.45	0.70	0.63	–0.31	–0.67	–0.62	–0.14
K_{st}	0.96	–0.23	–0.05	–0.20	–0.93	0.23	0.68	0.59	0.38
d, mm	–0.80	0.47	0.21	–0.82	0.35	–0.35	–0.90	–0.23	0.22
	Wet sieving								
> 3 mm	0.81	0.27	0.42	0.76	–0.39	0.08	0.84	0.10	–0.03
3–0.5 mm	0.75	0.52	0.32	0.96	0.10	0.07	0.86	–0.45	0.02
1–0.5 mm (a)	0.45	0.70	0.11	0.94	0.15	–0.01	0.79	–0.53	0.04
0.5–0.25 mm (b)	0.05	0.34	–0.89	–0.51	–0.72	–0.44	–0.39	0.23	0.46
b/a	–0.80	–0.55	0.11	–0.82	0.44	0.26	–0.83	0.41	–0.20
< 0.25 mm	–0.48	–0.51	–0.43	–0.95	–0.18	0.14	–0.83	0.38	0.11
> 0.25 mm	0.84	0.48	–0.18	0.85	–0.42	–0.25	0.87	–0.45	0.07
C_{ws}	0.16	–0.95	–0.04	–0.67	0.24	0.68	–0.03	0.74	0.08
d, mm	0.84	0.46	0.12	0.93	–0.36	0.01	0.89	–0.32	0.15
Expl.Var.	9.98	5.06	2.17	10.45	4.30	3.31	8.19	4.41	3.32
Prp.Total	0.50	0.25	0.11	0.52	0.22	0.17	0.41	0.22	0.17

There is a criterion of adequacy of the sample with respect to the factors, which makes it possible to characterize the degree of suitability of factor analysis to the given sample of quantitative indicators or variables (Kaiser-Meyer-Olkin test):

> 0.9 – unconditional adequacy;
> 0.8 – high adequacy;
> 0.7 – sufficient adequacy;
> 0.6 – satisfactory adequacy;
> 0.5 – low adequacy;
< 0.5 – lack of adequacy.

It was found that for plowing (F_1), there were 4 correlation coefficients > 0.9, 6 coefficients > 0.8, and 1 coefficients > 0.7. Out of these, 6 correlations were attributed to structural components, and 5 correlations were attributed to the components of water-resistant structure. Regarding F_2, a strong correlation was established with the group of water-resistant aggregates sized 1–0.5 mm ($R = 0.70$) and C_{ws} ($R = -0.95$). For F_3, the association was made with the fraction of water-resistant aggregates sized 0.5–0.25 mm ($R = -0.89$).

There were 33 correlation coefficients of low adequacy ($R < 0.05$) for F_1–F_3, which accounted for 71% of the total number of factor loadings.

For systematic surface tillage, regarding F_1, there were 9 correlation coefficients with $R = 0.7$–0.9 and 6 cases with $R = 0.5$–0.6. There were 2 correlation links of high adequacy level ($R = \pm$ 0.70–0.82) related to the dry sieve fractionation, while there were

6 correlation links of unconditional and high adequacy related to the water-stable aggregates fraction, and 1 correlation link with a sufficient adequacy level.

Regarding factor F_2, there was a connection at the level of unconditional adequacy with K_{st}(dry), and at the level of sufficient adequacy with the fraction of aggregates 7–0.25 mm and 0.5–0.25 mm (wsa). For other variables (13 links), the connections were at a low adequacy level. For F_3, at the level of unconditional and sufficient adequacy, there were correlations with the fractions of aggregates 5–3 mm (wsa) and 7–5 mm (dry).

In surface tillage, there were 6 links of satisfactory adequacy ($R > 0.6$), which is 6 times more than in conventional tillage. There were 27 cases of low adequacy and its absence in surface tillage, which is 1.22 times less or 12% less compared to conventional tillage.

In the No-till system, regarding F_1, there were 9 cases of links with adequacy ranging from $R > 0.7$ to $R > 0.9$, and 3 cases with $R > 0.5$. Regarding F_2, there is one connection (C_{ws}) with sufficient adequacy, while there were four connections of satisfactory and low adequacy. In the No-till system, there were 5 cases of links with unconditional, high, and sufficient adequacy for dry sieve fractionation, while for water-stable aggregates fraction, there were 8 cases. Links with low adequacy and lack of adequacy accounted for 55% of the total, similar to surface tillage.

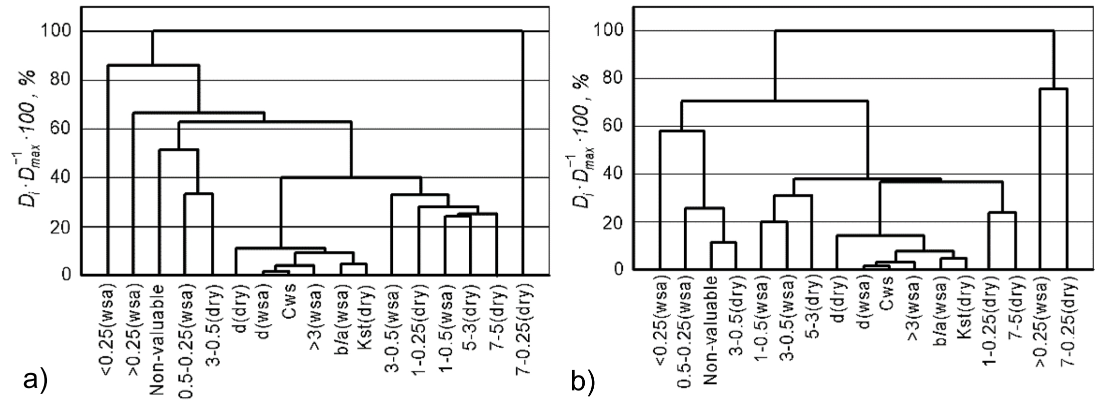
The consolidation of the components of the structural-aggregate composition of chornozem under different tillage systems is determined by links of sufficient to unconditional adequacy. In surface tillage and the No-till system, the same number of such links were created (13–14 cases), but in conventional tillage, the distribution ratio between components in dry and wet sieving was about 50% to 50%, while in surface tillage and the No-till system, the ratio was 1.3–1.6 to 1 in favor of water-stable aggregates. It is important to note the increase in links of satisfactory adequacy ($R > 0.6$), which were 5–6 times fewer in conventional tillage compared to surface tillage and the No-till system.

The principal component analysis revealed the main components of the structural-aggregate state, obtained under dry and wet sieving conditions, which determine the differences in soil structural condition under different tillage methods. Cluster analysis involves the use of distance matrices and the 'nearest neighbor' clustering algorithm to construct a dendrogram of grouping the components of the structural-aggregate composition under dry sieving and water erosion conditions (Vorobyov & Ladan, 2021).

The maximum cluster sizes are determined by half the distance between the most distant components based on the criterion $D_{\mathrm{i}} < D_{\max}/2$. The clustering results of the components of the structural-aggregate composition of leached chornozem, respectively, according to the distribution of dry structural aggregates and water-resistant aggregates, are shown in dendrograms (Fig. 3). Overall, the similarity measure based on the criterion of the largest cluster is 51.1% for plowing and surface treatment, and 48.8% for the No-till system (Fig. 3).

For plowing, three main clusters have been identified:

1. Cluster 1 – with the least dissimilarity (10.8%): *d*(dry), *d*(wsa), C_{ws}, K_{st}, > 3 mm (wsa), the ratio of 0.5–0.25 mm (wsa) to 1–0.5 mm (wsa);
2. Cluster 2 – with a similarity measure of 33.2% (7–5 mm (dry), 5–3 mm (dry), 1–0.5 mm (wsa), 1–0.25 mm (dry) и 3–0.5 mm (wsa));
3. Cluster 3 – with a similarity measure of 51.1% (3–0.5 mm (dry), 0.5–0.25 mm (wsa), non-valuable aggregates (dry)).



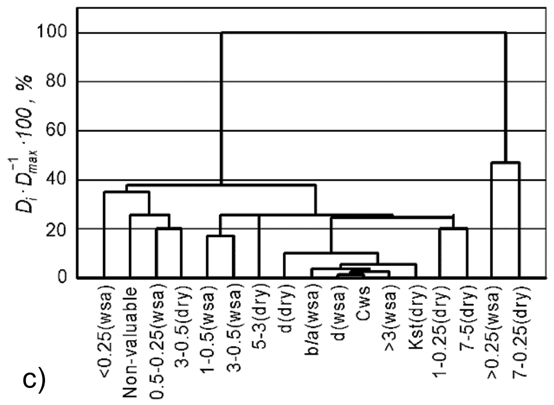


Figure 3. Dendrograms of clustering for the components of the structural-aggregate composition under different tillage methods: a – conventional tillage; b – surface tillage; c – No-till.

The similarity between clusters 1 and 2 was 40.5%, while between these clusters and cluster 3 it was 51.1%, which corresponds to the criterion of the maximum cluster. Beyond this point, further clustering loses its relevance. The identified fractions of 7–0.25 mm (dry), > 0.25 mm (wsa), and < 0.25 mm (wsa) stand out from the overall clustering of structural-aggregate components, indicating soil imbalance at the structural level as a system.

For surface tillage, the clustering of structural-aggregate state parameters follows a more complex pattern:

1. Cluster 1 – is similar to the cluster in conventional tillage, with increasing divergence up to 14.4%.
2. Cluster 2 – 1–0.5 mm (wsa), 3–0.5 mm (wsa), 5–3 mm (dry) – 19.4%.
3. Cluster 3 – 0.5–0.25 mm (wsa), non-valuable aggregates (dry) and 3–0.5 mm (dry) – 26.6%.
4. Cluster 4 – 1–0.25 m (dry) и 7–5 mm (dry).

The merging of these clusters occurs at a level of 37.5%, which is approximately 3% lower than in conventional tillage. The maximum criterion level of 51.1% excludes fractions > 0.25 mm (wsa) and 7–0.25 mm (dry) from the overall clustering, showing 86% similarity, and the fraction < 0.25 mm (wsa) with a 58.3% similarity level.

The decrease in the distance measure between clusters 1–3 compared to conventional tillage by about 3% indicates a certain stabilization of the soil structure under surface tillage.

In the No-till system, the clustering of soil structure elements during dry and wet sieving followed the same principle as surface tillage. Clusters 1–4 were merged at a level of 25.4%, which is 15.1% lower than in conventional tillage or approximately 1.6 times lower, and compared to surface tillage, it is 12.1% lower or approximately 1.48 times lower in total. At the similarity level of clustering features, 11 parameters (64.7%) were merged, whereas in conventional tillage, it was 6 parameters (35.3%), similar to surface tillage.

The maximum criterion value for the overall cluster in the No-till system was 48.8%. However, clusters 5 (< 0.25 mm (wsa), non-essential aggregates in dry sieving, 0.5–0.25 mm (wsa), 3–0.5 mm (dry)) and 6 (> 0.25 mm (wsa) and 7–0.25 mm (dry)) had distances of 38% and 46%, respectively, which did not exceed the value of the overall cluster (48.8%). This indicates that all components of the soil structure were involved in the overall clustering, which is a sign of optimization of the structural-aggregate state with the systematic use of the No-till system in the 5-field crop rotation.

The sustainable effect of using the No-till system is evident in the accumulation of mulch on the soil surface, which helps increase soil moisture content. With an increase in mulch mass from 1–2 t ha^{-1} to 8–10 t ha^{-1}, soil erosion losses are reduced. This is an effective way to increase soil moisture content, reduce the water consumption coefficient of crops, and reduce the consumption of productive water reserves for physical evaporation during the growing season of agricultural crops in a short rotation crop system (Tuure et al., 2021; Ye et al., 2024).

When creating a mulch layer on the soil surface, its influence is noted on both cultivated and uncultivated soil in preserving productive water reserves. It has been found that the content of productive water with No-till is higher than with soil tillage in 50% of cases, equal in 35%, and lower in 15%, which is associated with improved agrophysical indicators (Khera, 2006; Mulumba & Lal, 2008; Bhatt & Li et al., 2013; Blanco-Canqui & Ruis, 2018).

The impact of organic mulch on soil processes lies in improving parameters that contribute to its fertility, associated with the addition of additional organic matter and protection of the soil surface (Kibet et al., 2016¸ Vach et al., 2018). Negative assessments indicate soil compaction in the absence of tillage (Gozubuyuk et al., 2014), which is influenced by soil characteristics, climatic conditions, insufficient thickness or short duration of mulch use.

In semi-arid climates, soil water before autumn tillage was lower with tillage and shallow tillage at 22.4% and 12.8%, respectively, compared to No-till. However, three weeks after tillage, moisture levels were 21.1% and 14.3%, respectively. This can be explained by reduced evaporation and a 2.4 times increase in soil filtration coefficient due to increased vertical macropores (Dudchenko et al., 2014; Manushkina et al., 2020).

When comparing spring water reserves in 2023 to those in 2022, it was found that with tillage in the 0–1 m layer, there was a slight tendency towards accumulation, whereas with surface tillage over 7 years, water reserves in the 1 meter depth increased by 10 mm with growing water reserves in soil layers. With the No-till system, water reserves in the 1 meter depth relative to 2022 increased by 19 mm with a 13 mm increase in composite layers of soil thickness (0–0.5 mm) under plowing. Implementing No-till through surface tillage ensured an increase in water reserves in the 1 meter depth, reaching 14 mm.

In April 2022, the productive water reserves in the 0–1 m layer were at the same level regardless of tillage method, but with surface tillage, there was a decrease in productive water reserves by 8–10 mm. In June, water reserves in the 1 meter depth under the No-till system were higher by 7–9 mm, while in July, conversely, with plowing and surface tillage, moisture was higher by 5–7 mm. The expenditure of productive water reserves from the 1 meter depth for April–June increased with plowing by an average of 8–10 mm, while for June–July, it increased from plowing (–7.0 mm) to surface tillage (–16 mm) and the No-till system: –12.0 mm (with plowing) and –20 mm (with surface tillage). The expenditure of productive water reserves for April–July, regardless of the tillage method, was practically the same.

In 2023, the moisture expenditure for April–June with plowing was 120 mm with a ratio of expenditure from the sub-layers of 1.2 to 1. With the No-till system through plowing, the moisture expenditure was 112 mm (a decrease of 8 mm) with a ratio of expenditure of 1.64 to 1 (Table 7). With surface tillage and the No-till system through surface tillage, the moisture expenditure was 129–131 mm with a ratio of expenditure of 1.1 to 1. The highest water reserve was in June with the No-till system through plowing - 51 mm compared to 41 mm (tillage), 26 mm (surface tillage), and 42 mm (No-till through surface tillage).

Table 7. The impact of different tillage methods on the balance of productive water reserves in a 5-field crop rotation

Tillage method	Productive water reserves and consumption, mm					
	April	June	± April to June	July	± June to July	± April to July
	2022 year					
Conventional tillage (CT)	151.0	48.0	–103.0	41.0	–7.0	–110
No-till after CT	150.0	55.0	–95.0	43.0	–12.0	–107
Surface tillage (ST)	143.0	49.0	–94.0	33.0	–16.0	–110
No-till after ST	153.0	57.0	–96.0	37.0	–20.0	–116
	2023 year					
CT	161.0	41.0	–120.0	87.0	+46.0	–74.0
No-till after CT	167.0	55.0	–112.0	104.0	+49.0	–63.0
ST	157.0	26.0	–131.0	73.0	+46.0	–84.0
No-till after ST	171.0	42.0	–129.0	104.0	+62.0	–67.0
	2022–2023 years					
CT	156.0	45.0	–111.0	64.0	+19.0	–92.0
No-till after CT	160.0	55.0	–105.0	74.0	+19.0	–86.0
ST	150.0	38.0	–112.0	53.0	+15.0	–97.0
No-till after ST	162.0	50.0	–112.0	71.0	+21.0	–91.0
$LSD_{0.05}$	7.5	7.5	-	7.0	-	-

Note: (CT) – conventional tillage; (ST) – surface tillage.

The poorest water supply was observed with surface tillage – 26 mm with a layered distribution of 8 mm and 18 mm for ratios ranging from 0.4 to 1. The highest water supply was recorded with No-till under conventional tillage – 55 mm with a ratio of 0.36 to 1, with a water reserve in the 0.5–1 m layer of 41 mm, which is higher than with conventional tillage and No-till under surface tillage by 13 mm and 23 mm, respectively. Water intake during June–July with conventional tillage, No-till under conventional tillage, and surface tillage was 46–49 mm, whereas with No-till under surface tillage, it was 62 mm. Kibet et al. (2016) came to similar results when studying the influence of long-term tillage when studying organic components in the soil and its structure on Typic Argiudoll. Accumulation of water occurred in the 0–0.5 m layer, increasing from conventional tillage to 56 mm (+10 mm) with No-till under surface tillage (Table 3).

The water reserve in July in the 0–1 m layer was highest with No-till – 104 mm, which is 17 mm more than conventional tillage and 31 mm more than surface tillage. Tuure et al. (2021) when studying and modeling the soil moisture content when mulching the soil surface with plant residues, confirms these results. Water consumption from the 0–1 m layer during the growing season with conventional tillage and surface tillage was: –74 mm and –84 mm, respectively, while with No-till it ranged from –63 mm to –67 mm, significantly lower by –9 mm and –19 mm.

On average for 2022–2023, the productive water reserves in the 0–1 m layer in April with conventional tillage and surface tillage were almost the same, while with No-till, water reserves were significantly higher (+10–12 cm). In June, the productive water reserve was highest with No-till and lowest with surface tillage (–15 mm). Ye et al. (2024) obtained similar results when studying moisture reserves in the soil during mulching, but he had different climatic conditions.

In July, the productive water reserve in the 1 meter layer with no-till was higher by 9–10 mm compared to conventional tillage, while with surface tillage, it was 11.0 mm lower. Water consumption from the productive water reserve during June–July was highest with No-till under surface tillage (+21.0 mm) compared to +15 mm with surface tillage. Water consumption with conventional tillage and No-till under conventional tillage was the same. Overall, water consumption from the productive water reserve during April–July, regardless of the tillage method, was consistent: 86–97 mm.

CONCLUSIONS

1. The normalization of water-resistant aggregates sized 3–0.5 mm showed that their content, as per the median, was lower than the mean value during plowing, while during surface tillage and No-till, conversely, it was higher than the mean value, indicating a tendency for the content of this fraction to approach the upper typical value or to increase. The most valuable fraction of water-resistant aggregates (3–0.5 mm) was least abundant during plowing: 18.4% (0–0.2 m), 19.5% (0–0.3 m). During surface tillage, the increase in the content of aggregates sized 3–0.5 mm relative to plowing was 12% (0–0.2 m) and 8.1% (0–0.3 m), while with No-till farming, it ranged from 9.4% to 14.7% (0–0.2 m) and 11.0% to 13% (0–0.3 m), indicating the aggregation of swater-resistant aggregates into the most valuable fraction of water-resistant aggregates, thereby influencing a more rational utilization of the productive water reserve during the crop growing period in the crop rotation.

2. No significant pairwise correlation links ($R > \pm 0.7$) were found between the mean-weighted diameter of dry aggregates and the components of water-resistant structure during conventional tillage, whereas during surface tillage, there were 7 such links, including 2 direct and 5 inverse correlations. Similarly, under the No-till system, there were 7 correlations, comprising 2 direct and 5 inverse correlations, indicating the subordination of water-resistant structure components to the structural composition during dry sieving through the mean-weighted diameter of dry structural aggregates. The

presence of inverse correlations of strong correlation indicates a high level of self-regulation of the structural-aggregate state compared to plowing during surface tillage and the No-till system.

3. Under the No-till system (after 2–3 years of implementation), there is an accumulation of productive soil water in the 0–1 m soil layer by 8–12 mm more compared to conventional tillage. Relative to the water reserves in 2022, the water stock increased by +19.0 mm (after plowing) and by +14.0 mm (under surface tillage) in 2023. This is associated with the formation of mulch layers on the field surface and the creation of vertical channels by earthworms and vertical macropores from the decomposition of roots, which are not disrupted by intensive tillage.

4. Under the No-till system, in June and July, the average productive soil water reserve was higher compared to conventional tillage by 5–10 mm and 7–10 mm, respectively, over the period of 2022–2023. In comparison to surface tillage, the difference was even greater, with increases of 10–12 mm and 18–21 mm, respectively. In 2023, the productive soil water reserve in July under the No-till system exceeded that of conventional tillage by 17 mm and surface tillage by 31 mm. This improvement in soil moisture retention in June–July is attributed to the increase in water-stable aggregates sized 3–0.5 mm.

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