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STATE OF WATER-STABLE SOIL STRUCTURE IN THE CENTRAL FOREST-STEPPE UNDER AGROGENIC AND POSTAGROGENIC MAINTENANCE

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Aim. To determine the regularities in the formation of water-stable structure and to obtain the objective integral information about the process of break-up and consolidation of the water-stable structure under agrogenic and postagrogenic load on the main soil types of the Central Forest-Steppe of Ukraine. **Methods.** The field method – the soils of chernozem type were investigated (seven chernozem-like soil types of different granulometric composition and humus content) in the central part of the Forest-Steppe of Ukraine, the laboratory analytical method (wet sieving of soil structure), the mathematical-statistical method (non-parametric statistics, factor, cluster, and fractal analyses). **Results.** The analysis of the water stability of the structure of chernozem-like soils in the Forest-Steppe demonstrates the perspectives of using modern statistical methods: fractal, factor, cluster methods, and the method of non-parametric statistics, which demonstrates their sensitivity to insignificant changes in the distribution of water-stable aggregates within the agronomically valuable interval. The soil types of postagrogenic maintenance form the distribution of water-stable aggregates, making up "prevailing" sizes of aggregates in the interval of sizes of 5–3 and 2–1 mm, which ensures the persistent state of the re-distribution where the index of Hurst has the values of $H > 0.75$. The agrogenic impact on soils changes the re-distribution of water-stable aggregates, destroying their natural distribution and ensuring the antipersistent state of the distribution with low stability ($D > 1.43$ and $H < 0.58$). Under postagrogenic maintenance of soil types, there is a stable mutual connection between water-stable aggregates, structural units, and ESP ($R = +0.78$), and in the total of correlation relations, the direct and inverse correlation relations of $R > \pm\ 0.55$ level are >30 % with the 1.5 to 1 ratio in favor of inverse proportion relations which ensures a high level of self-regulation for the hierarchical organization of the structural and water stable state. **Conclusions.** The determining index, characterizing the stability level of the water-stable structure, was found to be the content of water-stable aggregates of 3–1 mm and > 0.25 mm and the weighted average diameter of water-stable aggregates within the agronomically valuable interval of sizes that demonstrated a strong correlation ($R = \pm 0.76–0.96 \pm 0.02$) with fractal dimensionality ($D > 1.4$) and the index of Hurst (H) which allowed for forming a gradation scale for the evaluation of the water-stable structure and the degree of agrogenesis manifestation of soils in the Forest-Steppe of Ukraine. In terms of the rate of agrogenesis manifestation via the formation of the degree of the water-stable structure, the soils of chernozem type were divided as follows: *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay < typical low-humus heavy-loamy light-clay chernozem on loess-like clay < meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay < typical medium-humus heavy-clay chernozem on loess.*

Key words: water-stable aggregates, agronomically valuable interval, fractal dimensionality, weighted average diameter, agrogenesis, water stability, ESP.

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INTRODUCTION

The water-stability rate of structural aggregates should be considered as a phenomenon, accumulating the result of the complex of soil formation processes. The combination of water-stable aggregates of different sizes and forms establishes the aggregate composition, whose evaluation, control, and maintenance of the optimal composition should become a prerequisite of any agricultural human activity (Medvedev et al, 2017). Soil aggregate composition is usually divided into two hierarchy levels: macroaggregate and microaggregate, which is supported by certain physical content, including different resistance of different categories of aggregates to destruction (Bulyhin et al, 2014). From the standpoint of soil science and agricultural estimation of the state of soils, the most relevant characteristic of the macroaggregate state is the resistance to destruction in a wet state, because the soil aggregate of chernozem should be water-stable which is directly dependent on the amount and quality of humic compounds. (Bulyhin et al, 2020; Demydenko, 2020; Medvedev, 2016). The water-stability of structural aggregates is a property, relevant from the agronomic standpoint, but it does not provide the complete characteristics of the structure quality, as two soils, similar in their structure, may differ in their quality. This difference depends on the conditions, in which water-stable aggregates are formed, and a special role here is played by humic compounds (Zhernova, 2016).

In many aspects, the water stability of aggregates is determined by the intensity of agricultural use of soil, because with the increase in the technogenic load, the water-stability of soil structure decreases (Tkachenko et al, 2016; Demydenko, 2019; Gajic et al, 2006; Six et al, 2000). The most important role in the formation and transformation of soil aggregates is attributed to movable organic matter. Some data state that easily mineralized organic matter (labile humic compounds) play the main role in the formation of water-stable soil structure, which is more present in macroaggregates and less – in the particles of < 0.25 mm (Chefetz et al, 2002; Jastrow, 1996; Six et al, 1998; Six et al, 2000; Medvedev, 2008; Panasenko, 2015).

It is known that the saturation of soil aggregates with water is a destructive factor because under fast wetting of soil, the air, coming out of the aggregate pores, creates high pressure, which destroys the aggregate (Panasenko, 2015).

The water stability of soil aggregates is determined by the content of organic carbon in them and has a direct effect on the structural state of soil and its physical properties. Organic compounds condition the strength of soil aggregates, decreasing their wettability and affecting their mechanic strength (Onweremadu et al, 2007).

In particular, the organic substance, bound to gleyic minerals, increases the degree of their hydrophobicity, which may explain the resistance of aggregates to wetting (Panasenko, 2015; Chenu et al, 2000). The composition of organic matter components and the resistance factors for microaggregates with different mechanic strength were studied in several investigation projects (Amato M, Ladd JN, 1992; Post WM, Kwon KC, 2008; Chenu C, Plante AF, 2006; Bronick CJ, Lal R, 2005; Ashamn et al, 2003).

The study of water-stability of the soil structure of arable soils under different soil use systems with different levels of agrogenic load is of great relevance for the evaluation of soil resistance to intense agricultural impact.

The water stability of structural units of soil types affects fertility as a whole. At the same time, the water stability of soil structure depends on many factors, including a crop under cultivation, its predecessor, soil tillage, humus content, the introduction of organic and mineral fertilizers, calcium content, and agrogenesis of the very soil types.

The study of the current agrogenic impact on water stability of the structure of the main soil types is urgent in the current soil-climatic conditions of the Forest-Steppe of Ukraine (Medvedev et al, 2017; Bulyhin et al, 2014; Degtyarev VV, Panasenko OS, 2013; Stationary, 2016; Degtyarev et al, 2020; Medvedev et al, 2015). In recent decades, the problem of the deterioration of water stability of arable soils has become more urgent. The situation is made worse by limited use of fertilizers, especially organic ones, and unregulated introduction of mineral fertilizers which causes the peptization of soil colloids and leads to the destruction of water-stable aggregates, enhancing the physical degradation of arable soils.

The novelty of the studies lies in the fact that current statistical analysis of the data of wet sieving of structural units of different soil types in the Right-Bank and Left-Bank Forest-Steppe under agrogenic and postagrogenic use allows for determining deeper functional connections between different hierarchical levels of organization of soil structure simultaneously, which ensures obtaining new objective and integral information about the direction of agrogenesis under technogenic and aerogenic load.

The aim of the study. To determine the regularities in the formation of the water-stable structure and to obtain the objective integral information about the process of break-up and consolidation of the water-stable structure under agrogenic and postagrogenic load on the main soil types of the Central Forest-Steppe of Ukraine.

MATERIALS AND METHODS

Seven objects, located in the Right-Bank and Left-Bank Forest-Steppe of Ukraine, were selected for the study.

Object No. 1. A permanent experiment of the O.I. Dushechkin Department of Agrochemistry and Plant Production Quality of the National University of Life and Environmental Sciences of Ukraine, which was launched in 1956. (50º47’ north. latitude, 30º 23’ east. longitude, 180 m above sea level) (Medvedev et al, 2015) in the Right-Bank Forest-Steppe. The soil of the experimental plot: No. 1 – *meadow-chernozem low-humus carbonate heavy-loamy medium-clay on loess-like clay*. The arable layer contains 4.09 % humus, 270.0 mg/kg – labile phosphorus, 89.3 mg/kg – exchange potassium. The experiment was done in three repeats. The sowing area – 172 sq.m., the registration area – 100 sq.m. The fertilizers used in the experiment: ammonia nitrate (34 %), granulated superphosphate (19.5 %), potassium chloride (60 %) according to the elaborated scheme (Table 1).

Object No. 2. The multifactor experiment of the Department of Agronomic Soil Science and Soil Microbiology, the NSC “Institute of Agriculture”, the NAAS (50º26’13” north latitude, 30º30’20” east longitude, 120 m above sea level), launched in 1992. According to the agroclimatic zoning of Ukraine, it is situated in the northern subprovince of the Right-Bank Forest-Steppe in the Kyiv agrosoil area. The soil of the experimental plot: No. 2 – *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay*. Initial soil parameters (0–20 cm): total humus – 1.44 %, pH_{KCl} – 4.6, hydrolytic acidity – 3.6 mg-eq/100 g of soil, exchange calcium and magnesium – 3.9 and 0.58 mg-eq/100 g of soil, alkaline hydrolyzable nitrogen – 71 mg/kg, labile phosphorus – 223 mg/kg, exchange potassium – 120 mg/kg. The system of mineral fertilization in the experiment includes three doses (from ordinary to double dose) – 160, 240, and 320 kg/ha NPK, organic fertilization – 10 t/ha of manure in the first rotation, by-products (straw of cereals), clover cover crop – in the second and third rotations. Lime was added in 1992 and 2005 in the 1.0 and 1.5 doses by hydrolytic acidity (1.0 Ha = 5 t/ha $CaCO_3$) (Table 1).

Object No. 3. The multifactor experiment of the Panfylska Experimental Station, NSC “Institute of Agriculture”, the NAAS, (50º13’22” north latitude, 34º44’46” east longitude, 128 m above the sea level) was launched in 2000 in the Left-Bank Forest-Steppe, situated in Yahotyn District, Kyiv Region. The soil of the experimental plot: No. 3 – *typical low-humus heavy-loamy light-clay chernozem on loess-like clay*. According to the data of agrochemical analysis of the initial samples, the content of humus in the arable layer varies from 3.08 to 3.15 %, in the subarable layer – from 2.72 to 2.9 %. The soil is characterized by a content of phosphorus – 233–270 mg/kg of soil in the arable layer (0–20 cm) and 227–270 mg – in the subarable layer (20–40 cm); increased (by Chirikov) or moderate (by Machygin and Kirsanov) content of exchange

Table 1. The schemes of multifactor field experiments

Meadow-chernozem low-humus carbonate medium-clay heavy-loamy soil on forest-like clay		Gray forest low-humus heavy-loamy light-clay on carbonate loess-like clay		Typical low-humus chernozem, heavy-loamy light-clay on loess-like clay	
Object No. 1		Object No. 2		Object No. 2	
Sugar beet following spring wheat	Control (no fertilizers) $N_{100}P_{95}K_{90}$ $N_{120}P_{110}K_{100}$	Spring wheat following soybeans	Control (no fertilizers) *1.0 Ha $N_{65}P_{60}K_{70}$ $CaCO_3$	No-till	$N_{90}P_{75}K_{90}$ $N_{120}P_{85}K_{115}$
Clover 2nd year	Control 1 (no fertilizers)		*1.0 Ha $N_{90}P_{75}K_{85}$ + CaCO3	Ploughing	$N_{90}P_{75}K_{90}$ $N_{120}P_{85}K_{115}$
Clover 2nd year	1.5 NPK	–	–	–	–

Note. Ha – hydrolytic acidity, mg-eq. per 100 g of soil potassium (80–100 mg/kg of soil) (Medvedev et al, 2015). The reaction of soil solution was weak-acid, the saturation rate of the absorbing complex with alkali was high (85–99 %).

The schemes of long-term experiments on soil types Nos. 1–3 are presented in Table 1.

Object No. 4. In 1990–1996, there was a study of long-term effect of soil tillage on the restoration of the structural state of typical chernozems in agrosystems of the Eastern Forest-Steppe in the Southern Poltava agroecologic area. The study was conducted by the Department of Soil Science and Soil Protection, the NULES. The soil: No. 4 – *typical medium-humus heavy-loamy chernozem on loess*. By the content of physical clay (PC) and physical sand (PS), chernozem may be referred to light clay: PC = 62.9–64 %; and PS = 35–37.1 %. The structural state was investigated in the field, where ploughing for different depths had been conducted for over 80 years with the introduction of 8 t/ha of manure +$N_{90}P_{90}K_{80}$, the ploughing variant for 10 years in the experiment with the introduction of 10–12 t/ha of manure + $N_{90}P_{90}K_{80}$ in the 10-field crop rotation with subsurface tillage of different depth with the introduction of 10–12 t/ha of manure +$N_{90}P_{90}K_{80}$.

Object No. 5. The additional statistical analysis of the components of the structural state and water stable structure involved the use of the literature data (Degtyarev VV, Panasenko OS, 2013), received in the Rohan permanent establishment of the Kharkiv National Agrarian University named after V.V. Dokuchaiev. The soil: No. 5 – *typical medium-humus heavy-loamy chernozem on loess-like clay*. The geographic coordinates of the experimental field of the Agrochemistry Department: 49˚54′12.61″ north latitude and 36˚26′24.71″ east longitude. Soil samples were taken from the fallow and ploughed layer.

Object No. 6. The analysis also involved the data about the distribution of water-stable chernozem aggregates of the division of the Ukrainian Natural Steppe Reserve – "Mykhailivska Tsilyna", presented as *typical heavy-humus medium-clay chernozem on loess-like clay.* The physical and agrochemical properties of chernozems Nos. 5–6 are specified at the reference (Degtyarev VV, Panasenko OS, 2013).

Object No. 7. The study of the structural state and water-stable structure of the fallow (35 and 45 years) and ploughed soil (>75 years) was conducted in the Middle Dnieper-Seym agrosoil district. The experiment was started in the Drabiv agrosoil district in the Forest-Steppe zone of the Left-Bank lowland province, northern subprovince. The soil cover consists of: object No.7 – *typical low-humus (humus content of 3.81–3.89 %) light-clay chernozem on loess*. The structuredness index (SI) is SI = 25–38 %. The ratio between physical sand (PS) and physical clay (PC) is 1.76–2.52, which is 3.2 times higher, and the factor of potential aggregation (FPA): FPA = 0.25–0.27, which is 2.78–2.96 times lower than in typical medium-humus light-clay chernozem on loess.

The methods of determining the structural state of soils. To determine the changes in agrochemical, physical, chemical, and agrophysical indices, and humus and agrophysical conditions, mixed samples were selected from one meter-deep soil layers in 10 cm distance following the schemes of experiments. The structural-aggregative composition was determined by the sieve method, modified by N. I. Savinov, and the water stability of the structure – by the method of I. M. Baksheev. For the soil fractioning in the air-dried state (dry sieving), a sample of up to 2.5 kg was taken from the soil in the air-dried state, (the acceptable weight is 0.5 kg) and sown on the column of sieves with the following diameters: 10, 7, 5, 3, 2, 1, 0.5, 0.25 mm. A fraction under 0.25 mm was collected into the bottom. The soil was sown into fractions: >10, 10–7, 7–5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25, and <0.25 mm. Each fraction was collected, and the percentage of its content was calculated. The entire weight of the soil was accepted as 100 %.

To determine the water stability, the average sample of 50 g was collected from all the fractions of structural units, obtained for dry sieving, in the amount of half the content percentage (a total of 25 g). Then the rocking sieves were used (Baksheev's method) on a device with a column of sieves of 5, 3, 1, 0.5, and 0.25 mm, the batch was transferred to the upper sieve, and water was poured to fill it. The sieves were rocked on the device for 12 min. Then a fraction of water-stable aggregates was transferred from each sieve onto the paper filter. The filters were dried to the air-dried state, and the percentage of fractions was calculated similarly to the air-dried state.

The granulometric composition was defined accor-ding to N. A. Kachynsky. In addition to dry sieving of soil according to N. I. Savinov, the sieving of fraction < 0.25 mm was done on the sieves with the diameters of 0.5; 0.25; 0.2; 0.16; 0.125; 0.1; 0.072; 0.05; and the bottom of < 0.25 mm. Each fraction of aggregates was weighed, and the percentage of its content in the total weight of the sample was calculated (Bulyhin et al, 2014).

The soil structure is agronomically valuable for dry sieving of 10–0.025 mm; water-stable aggregates with the pores of at least 40 %, the size of > 0.25 mm, the content of which conditions the physical state and biological activity of soil (Medvedev, 2017; Medvedev, 2016; Panasenko OS, Degtyarev VV, 2015).

The content of total humus was determined according to I. V. Turin in the modification of M. V. Simakov; pH_{KCl} – potentiometrically; hydrolytic acidity – according to H. Kappen in the modification; the total of absorbed alkali – by the method of Kappen); the degree of saturation with alkali – via calculations; easily hydrolyzed nitrogen – by Kornfeld. In chernozem soils (Chirikiv's method), labile phosphorus was determined photocolorimetrically; exchange potassium – by flame photometry in the modification of the NSC ISSAR. According to M.M. Miroshnychenko et al (2022) the method of phosphorus determination is compatible with the method of Mehlich 3 and Olsen ($R^2 = 0.65–0.75$).

The content of mineral nitrogen was determined by the photometric method with Nessler's reagent. In gray forest soils, labile phosphorus and exchange potassium were determined by Kirsanov's method, and in carbonate soils – by Machygin's method. The fractal evaluation of the distribution rows of structural units was conducted according to K.G. Moiseev (2014) and B.V. Kiselev (2007). The cluster and factor evaluation of the parameters of water-stable soil structure was conducted according to A.V. Kholodov (2016) and the reference (Stationary, 2016). The study results were generalized in Statistica-10 using non-parametric statistics, correlation, and factor analysis.

RESULTS OF INVESTIGATIONS

While studying the water stability of the soil structure, it is common to isolate water-stable aggregates of different sizes with the further calculation of the water stability coefficient (Bulyhin et al, 2014) and the average diameter of water-stable aggregates. It is important to conduct comparative re-distribution of water-stable aggregates within the agronomically valuable interval of sizes in soil types of postagrogenic maintenance and agrogenic load. This approach is relevant from both theoretical and practical standpoints. Under postagrogenic maintenance of different soil types, we found common regularities in the distribution of water-stable aggregates within the agronomically valuable interval of sizes (10–0.25 mm). There appeared two peaks of the formation of water-stable aggregates – 5–3 mm and 2–1 mm. In the first interval of sizes, the content of aggregates was 10–17 %, and in the second one – 18–24 % i.e. the distribution curves had a double-humped nature with the manifestation of the discrete sequence of the distribution (Fig. 1).

The exponential equations of distribution trends have a similar character: regression coefficients (R) with the variable had values in the range of 0.06x–0.12x with the reliability coefficient of $R^2 = 0.35–0.39$. Only the distribution of water-stable aggregates in soil types of the southern Left-Bank Forest-Steppe was set by the exponential equation with the reliability of the distribution trend equation with $R^2 = 0.67$ and the regression coefficient of 0.22x which is twice higher as compared to the abovementioned soil types. Under postagrogenic maintenance of soil types, the number of microaggregates of < 0.25 mm was 20–30 %.

Under agrogenic impact on soil types, the distribution of water-stable aggregates changes radically as compared to the average determined distribution under postagrogenic distribution (Fig. 1, *b*). The double-humped nature of the distribution of water-stable aggregates vanishes. There is an increase in the build-up of the content of fractions of < 0.25 mm to 35–50 % and the formation of fractions of water-stable aggregates in the interval of sizes of 1–0.25 mm. The exponential equations of trends have a reliable high rate ($R^2 = 0.88–0.98$).

The fractal evaluation of the distribution rows of water-stable aggregates demonstrated that under postagrogenic maintenance of soil types according to fractal dimensionality (D), the distribution of the water-stable structure becomes stable: D = 1.06–1.22, and according to H index (the index of Hurst) – to the persistent distribution (H > 0.5) or trend-stable state (Table 2).

Under the agrogenic load, the state of the distribution of water-stable aggregates according to D indices was on the stability threshold (D = 1.4–1.6): soil types of gray forest soil and typical heavy-clay chernozems (D = 1.45–1.49), whereas the soil type of typical low-humus chernozem is in the state of unstable distribution of water-stable aggregates (D > 1.6). Only the soil type of meadow-chernozem carbonate low-humus on loess-like clay was in a stable (persistent) state according to the distribution of water-stable aggregates, which will be preserved in the future.

According to H index, all soil types had a persistent distribution of aggregates (H > 0.5), only the soil type of typical low-humus heavy-loamy light-clay chernozem on loess had the distribution of water-stable aggregates which corresponded to an antipersistent or unstable

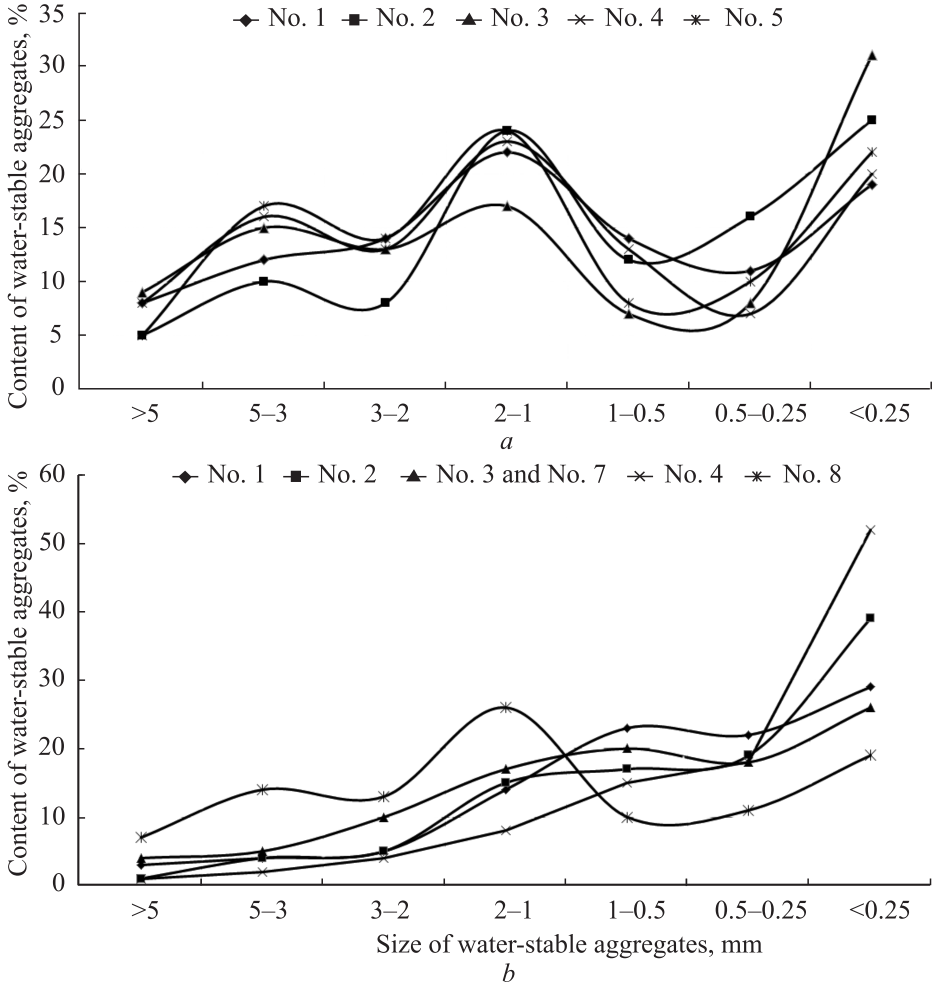

Fig. 1. The re-distribution of water-stable aggregates within the agronomically valuable interval (10–0.25 mm): *a* – fallow and virgin soil of soil types for No. 1–2 and 4.5–6.7 (No. 5 – the average content of water-stable aggregates for the Rohan multifactor experiment and Myhailivska Tsilyna) according to the list below. *b* – soil objects of agrogenic use: 1 – *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay*; 2. – *meadow-chernozem low-humus carbonate heavy-loamy medium-clay on loess-like clay*; 3 – *typical low-humus heavy-loamy light-clay chernozem on loess-like clay*; 4 – *typical medium-humus heavy-loamy chernozem on loess*; 5 – *typical heavy-clay chernozem on loess-like clay*; 6 – *typical high-humus medium-clay chernozem on loess-like clay* (Mykhaylivska Tsilyna); 7 – *typical low-humus light-clay chernozem on loess*; 8 – average re-distribution of aggregates with water-stable structure while maintaining fallows and virgin soil for Nos. 1–2 and 4–7

state. The degree of correlation (C) between fractions of water-stable aggregates under postagrogenic maintenance was on the level of strong correlation (C=0.65–0.84), while under agrogenic load of soil types, the degree of correlation between fractions was low (C=0.01–0.25), which approximates the state of the soil system to the stability threshold.

The factor analysis allows for determining the relevance of fractions of water-stable aggregates in the formation of the structural-aggregate state of soil. The direction of the correlation coefficients is used to determine the functionally direct role of water-stable aggregates: R ≥ ≥ 0.70, and that of inverse action – R≥ –0.70, which sets the level of self-regulation for the soil structure as a system (Sena et al, 2002). Under the postagrogenic maintenance, the load by factor F_1 is created by 6 fractions, including 4 of direct action and 2 of inverse action. The load by factor F_2 was created by 3 fractions of aggregates, including 2 of direct action and 1 of inverse action. In total, 9 fractions of water-stable aggregates relate to factors F_1 and F_2 (dispersion of 66 %), 6 of which are of direct action on F_1 and F_2, and 3 – of inverse action (the ratio of 2 to 1), which demonstrates a high level of balance in the water-stable structure (Table 3).

The agrogenic effect disrupts the factor load on the groups of aggregates. By factor F_1 the relation to aggregates of <0.25 mm is of inverse correlation. By F_2 the factor load is done by six fractions: 5–3, 3–2, 2–1, 3–1 mm by direct functional relation and with fractions 0.5–0.25 and 1–0.25 mm under the total dispersion of 49 %, which is 1.34 times less.

Under the postagrogenic maintenance, the relevant groups of water-stable aggregates are as follows: >5, 3–2, 2–1, 3–1, 1–0.5, 0.5–0.25, >0.25 and <0.25 mm, which makes a total of 8 fractions. Under the postagrogenic maintenance, the relevant fractions are as follows: 5–3, 3–2, 2–1, 3–1, 0.5–0.25, 1–0.25 and <0.25 mm that makes seven fractions with the load by F_2, which demonstrates the loss of balance in the water-stable structure. The factor analysis demonstrated that the agrogenic load destroys the level of organization of the structural-aggregate state, whereas the maintenance

Table 2. The values of fractal dimensionality as an indicator of the stability of the distribution of water-stable aggregates in the soils of the Forest-Steppe of Ukraine

Effect	$Y=ae^{bx}$ ($bx = \delta$)	Fractal indicator δ	Fractal dimensionality, $D=1-\lvert\delta\rvert$	Index of Hurst, $^*H=2-D$	Correlation measure, $C=2^{2H-1}-1$
Meadow-chernozem low-humus carbonate heavy-loamy medium-clay on loess-like clay					
Agrogenic	$Y=3.11e^{0.34x}$	0.34	1.34	0.66	0.25
Postagrogenic	$Y=10.1e^{0.06x}$	0.06	1.06	0.94	0.84
Gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay					
Agrogenic	$Y=1.67e^{0.45x}$	0.45	1.45	0.55	0.08
Postagrogenic	$Y=10.7e^{0.07x}$	0.07	1.07	0.93	0.82
Typical low-humus heavy-loamy light-clay chernozem on loess-like clay					
Agrogenic	$Y=0.57e^{0.63x}$	0.63	1.64	0.36	0.25
Typical low- and medium-humus medium- and heavy-loamy chernozems on loess					
Agrogenic (No. 3,4)	$Y=1.28e^{0.49x}$	0.49	1.49	0.51	0.01
Postagrogenic (No. 4–7)	$Y=5.25e^{0.22x}$	0.22	1.22	0.78	0.72
Average value for postagrogenic and virgin soil effect					
Postagrogenic	$Y=9.22e^{0.09x}$	0.09	1.09	1.09	0.77

Note. $^*0.5 < H < 1.0$ – persistent or trend-stable rows, 2) $H = 0.5$ – index of Hurst indicates a random row, 3) $0 < H < 0.5$ – range, corresponding to antipersistent rows (“returning to the average”).

Table 3. The factor load of separate components of water-stable soil structure in the state of postagrogenic and agrogenic load

Sizes of aggregate groups, mm	Fallows, virgin soil		Agrogenic effect	
	F – 1	F – 2	F – 1	F – 2
>5	**–0.79**	0.29	0.37	0.51
5–3	–0.53	0.44	0.48	**0.70**
3–2	**–0.81**	0.52	0.40	**0.74**
2–1	0.16	**0.80**	0.49	**0.70**
3–1	–0.48	**0.81**	0.50	**0.80**
1–0.5	**0.70**	0.04	0.25	–0.40
0.5–0.25	**0.89**	–0.13	–0.03	**–0.74**
1–0.25	**0.86**	–0.08	0.13	**–0.80**
>0.25	**0.80**	–0.00	0.57	0.26
<0.25	0.02	**–0.93**	**–0.77**	–0.22
Prp.Totl	0.46	0.20	0.29	0.22

in the state of fallow and virgin soil increases the structural organization to a high level.

The statistical evaluation of the normalized parameters for the content of different fractions of water-stable aggregates demonstrated that under the postagrogenic maintenance, the average content of agronomically valuable aggregates was at a level close to 85.0 %. The amplitude and normalized interval were narrowed. The variation coefficient for the most valuable fractions (3–1 mm) was 23.2 %, and that for 0.5–0.25 mm – 26.2 %. Under the agrogenic load, the average content of water-stable aggregates of the most valuable fractions decreased 4.3 times (> 5 mm); 2.88 times (5–3 mm); 1.45 times (3–1 mm), and the content of small fractions increased 1.9; 1.62; 1.18 times corresponding to the fractions of 1–0.5, 0.5–0.25 and < 0.25 mm. Here the variation coefficient of the most valuable fraction of water-stable aggregates (3–1 mm) increased 2.28 times, and that of microaggregates < 0.25 mm – 1.22 times (Table 4).

The amplitude and normalized interval for the content of some fractions of water-stable aggregates under the agrogenic load is considerably expended as compared to the postagrogenic maintenance. Here the value for the content of water-stable aggregates by the median mostly tends towards the lower typical value, whereas under the postagrogenic state, it tends to the typical upper value, which is related to the increase in the content of the most valuable water-stable aggregates and demonstrates the manifestation of natural soil formation (Table 4).

The differences in the quality state of the water-stable structure under the postagrogenic maintenance and agrogenic load is confirmed by the clusterization of specific groups of water-stable aggregates (Fig. 2).

Under the postagrogenic maintenance, there is clusterization of the most valuable water-stable aggregates at the level of 20 % of similarity, and smaller fractions – at the level of 10–12 % of similarity. All the presented groups of water-stable aggregates form a general total cluster which confirms a high level of self-organization and the integrity of their combination.

Under the agrogenic load of soil types, there is growing oddness in the formation of clusters and their

Table 4. The normalized statistical parameters for the structural composition of soil types of the Forest-Steppe under postagrogenic and agrogenic load

Size of aggregates, mm	Content of water stable aggregates, %						Coefficients		
	Mean	Median	Amplitude interval		Normalized interval		*CoefVar.,%	**Skewness	***Kurtosis
			Min.	Max.	$L_{0.25}$	$L_{0.75}$			
			Δ_a=Max–Min		$\Delta h= L_{0,75}–L_{0,25}$				
Fallows and virgin soil (No. 4–7)									
>5	9.56	10.9	0.30	16.3	1.50	15.2	63.6	–0.53	–1.31
5–3	8.17	9.21	1.30	14.8	4.80	9.68	49.4	–0.19	–0.64
3–1	29.5	29.9	14.2	42.4	28.4	34.4	23.2	–0.54	1.28
1–0.5	10.5	10.4	6.22	20.0	7.30	11.7	39.1	1.05	0.70
0.5–0.25	12.0	9.71	3.61	30.5	5.09	16.9	66.4	1.08	0.63
>0.25	84.6	80.5	65.9	133.8	67.7	87.5	26.2	1.72	2.23
<0.25	29.7	31.9	17.8	49.7	24.4	34.0	27.7	0.68	1.55
Agrogenic load (No. 1–4 and No. 5, 7)									
>5	2.22	1.12	0.00	15.9	0.59	2.26	139.8	2.69	7.41
5–3	2.84	1.95	0.06	12.2	1.10	3.99	87.8	1.60	2.56
3–1	20.4	19.6	3.54	50.7	11.7	28.3	51.8	0.51	–0.35
1–0.5	20.2	20.3	5.41	40.4	14.4	24.9	34.8	0.37	–0.07
0.5–0.25	19.4	18.8	7.34	50.8	14.1	22.6	44.0	1.52	3.25
>0.25	70.0	69.1	45.5	102.0	61.9	76.2	15.3	0.54	0.31
<0.25	34.99	33.6	5.74	58.9	26.4	44.3	33.7	–0.11	–0.62

Note. *Coef.Var., % – variation coefficient; ** Skewness – asymmetry; ***Kurtosis – excess.

remoteness in terms of similarity. For instance, the most valuable water-stable aggregates are clustered at the level of 10 % and smaller ones form clusters by size with growing remoteness in terms of similarity that reaches up to 50 %, which proves the imbalance in the combination of agronomically valuable water-stable aggregates, the correlation interrelation between which is weakened.

According to the conclusions of (Bulyhin et al, 2014), the development of soil structure which is in an imbalanced state due to the agrogenic effects is done rhythmically via the establishment or destruction and goes on interdependently on macro- and microlevels, and the results of the agrogenesis manifestation in the structural-aggregate state of soil are seen in the orderly hierarchical level of structural organization.

To confirm this conclusion, the matrices of paired correlation coefficients between the results of air-dry sieving with fractioning of microaggregates (fraction of < 0.25 mm) and the content of fractions of water-stable aggregates on different soil types in postagrogenic state and agrogenic load were calculated (Table 5).

Under the postagrogenic maintenance, there were 12.8 % of direct and inverse correlation relations R ± >0.50 in the block of water-stable aggregates, with the block of structural units – 10.2 %, and with the block of elementary soil particles (ESP) – 10.3 %. There was a total of 33.3 % of correlation relations of the mentioned level. The ratio between the correlation relations of direct and inverse effect in the block of water-stable structure and with the block of structural units was 1.2 to 1, with the block of ESP – 4.12 to 1; and as a total – 1.31 to 1. The presence of a large amount of inversely functional relations demonstrated a high level of self-organization of soil structure in the hierarchical mutual establishment of relations.

This regularity is radically disrupted for *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay*. The number of relations R ± >0.50 increases up to 15.2 %, while there are no relations with the block of structural units or the block of ESP. The total number of high-level relations was 2.2 times lower than the number of relations under the postagrogenic maintenance of chernozems. The self-regulation of the interaction between the blocks occurs due to the correlation relations R ± <0.50 %, which demonstrates a low level of stability for soil type of gray forest soil.

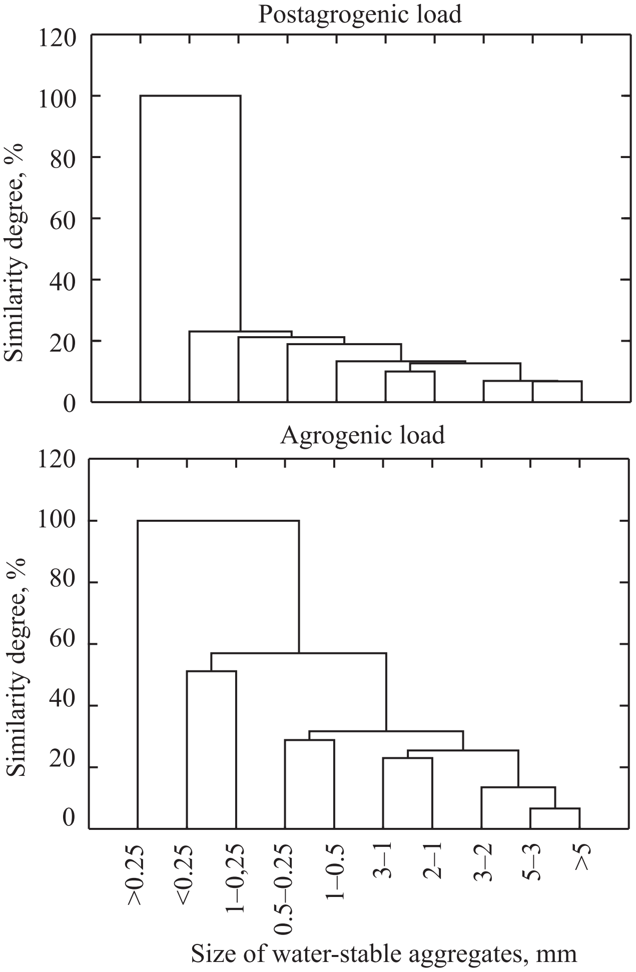

Fig. 2. The clusterization of the groups of water-stable aggregates of different sizes under postagrogenic maintenance and agrogenic load of soil types of the Forest-Steppe of Ukraine (X axis – sizes of water-stable aggregates, mm)

For *meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay,* the number of correlation coefficients (R ± >0.50) regarding the block of water-stable aggregates was at the level of the previous soil type at the ratio of direct and inverse relations of 1.15 to 1, which is 1.13 times lower as compared to the postagrogenic maintenance of the soil type. There were twice fewer direct and inverse relations of R ± >0.50 level of water stable aggregates with structural units as compared with postagrogenic maintenance. The total number of correlation relations of R ± >0.50 was found to be 1.7 times lower, and the ratio between the inverse relations and direct ones was 1.12 to 1, which is considerably lower as compared to postagrogenic maintenance.

The soil type of *typical low-humic heavy-loamy light-clay chernozem on loess-like clay* had 14.4 % direct and inverse relations of the level R ± >0.50 at the ratio of 0.75 to 1 in terms of the block of water-stable aggregates. As for the block of structural units,

Table 5. The effect of postagrogenic maintenance and agrogenic load on the percentage re-distribution of paired correlation coefficients of different strength and direction in the blocks of the aggregate-structural state of soil types of the Forest-Steppe zone

Level of correlation relations, R ±	Blocks of structural-aggregate state: % of correlation coefficients			Total n = 195 100%
	Water-stable aggregates n = 45 23.1%	Structural units n = 80 41.0%	Elementary soil particles (ESP) n = 70 35.9%	
Fallows and virgin soil (No. 1–7)				
< 0.50	*4.80	30.8	21.4	57.4
	**5.50	0.0	4.18	9.68
0.50–0.70	1.00	4.10	3.10	8.20
	2.60	4.60	6.20	13.3
0.70–0.95	4.60	0.50	1.02	6.20
	4.60	1.02	0.0	5.60
Total > 0.5	5.60	4.60	4.12	14.4
	7.20	5.62	6.20	18.9
R ± > 0.50	12.8	10.2	10.3	33.3
Gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay				
< 0.50	8.20	8.80	3.60	20.6
	–	5.1	0.50	5.60
0.4–0.5	–	3.59	3.01	6.60
0.50–0.70	3.10	0.0	0.0	0.0
	3.90	0.0	0.0	0.0
0.70–0.95	4.60	0.0	0.0	0.0
	3.60	0.0	0.0	0.0
Total > 0.5	7.70	0.0	0.0	0.0
	7.50	0.0	0.0	0.0
R ± > 0.5	15.2	0.0	0.0	15.2
Meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay				
< 0.50	3.10	11.3	35.9	50.3
	2.05	5.64	0.0	7.69
0.4–0.5	1.03	5.64	0.0	6.68
0.50–0.70	3.08	2.05	0.0	5.13
	3.59	2.05	0.0	5.64
0.70–0.95	3.59	0.0	0.0	3.59
	4.08	0.0	0.0	4.08
Total > 0.5	6.67	2.05	0.0	8.72
	7.67	2.05	0.0	9.72
R ± > 0.5	14.3	5.10	0.0	19.4
Typical low-humus heavy-loamy light-clay chernozem on loess-like clay				
< 0.50	9.20	25.0	31.7	65.9
	7.75	25.1	0.0	32.8
0.50–0.70	2.56	4.10	0.0	6.66
	2.56	5.13	4.1	11.8
0.70–0.95	5.64	4.62	0.0	10.3
	3.59	2.05	0.0	6.64
Total > 0.5	8.20	8.72	0.0	16.9
	6.15	7.18	4.1	17.4
R ± > 0.5	14.4	15.9	4.1	34.4

Finished Table 5

Level of correlation relations, R ±	Blocks of structural-aggregate state: % of correlation coefficients			Total n = 195 100%
	Water-stable aggregates n = 45 23.1%	Structural units n = 80 41.0%	Elementary soil particles (ESP) n = 70 35.9%	
Typical medium-humus heavy-loamy chernozem on loess-like clay				
< 0.50	11.3	37.3	35.4	84.0
	0.0	2.16	0.5	2.66
0.50–0.70	2.56	2.05	0.0	4.61
	5.64	1.54	0.0	7.18
0.70–0.95	3.08	0.0	0.0	3.08
	0.51	0.0	0.0	0.51
Total > 0.5	5.64	2.05	0.0	7.69
	6.15	1.54	0.0	7.69
R ± > 0.5	11.8	3.59	0.0	15.4

Note. *numerator – direct correlation; **denominator – inverse correlation.

the number of relations was 15.9 %, which is 1.5 times higher than the value for the postagrogenic maintenance at a ratio of 0.82 to 1. A water-stable structure formed 4.1 % of inverse direction with the ESP block. The total number of correlation coefficients R > ± 0.50 was at the level of soil types under postagrogenic maintenance (+1.1 %) at the ratio between inverse and direct relations of about 1 to 1.

In *typical medium-humus heavy-loamy chernozem on loess-like clay* in the southern Left-Bank Forest-Steppe, there were 1 % fewer correlation relations of R> ± 0.50 level between the groups of water-stable aggregates as compared to the postagrogenic maintenance. The ratio between inverse and direct relations was 1.1 to 1. It was found that there were 2.84 times fewer correlation relations with the block of structural units as compared to the postagrogenic maintenance at the ratio of 0.75 to 1. No correlation coefficients of R> ± 0.50 level were found with the ESP block. The relation to the water-stable structure was determined by the relations of R< ± 0.50 level. The total number of correlation relations of R > ± 0.50 level was 2.2–2.3 times lower as compared to *typical low-humus heavy-loamy light-clay chernozem on loess-like clay* and postagrogenic maintenance of chernozems.

For better substantiation of the conducted analysis of the structures of matrices of paired correlation relations, the regression equation between the components of the block of water-stable aggregates and the components of air-dried aggregates and components of ESP block was calculated (Table 6).

When soil types were kept in the state of fallow and virgin soil, a direct correlation was found between the content of water-stable aggregates of 3–1 mm and the content of structural units of 3–0.5 mm, and the correlation with structural units of 0.5–0.25 mm was inverse. The unit of the increase in the number of water-stable aggregates of 3–1 mm corresponded to the increase in the number of air-dried aggregates of 3–1 and 1–0.5 mm per 0.41–0.56 units.

The highest correlation coefficient was found between the content of water-stable aggregates of 3–1 mm and the ESP content of 0.125 and 0.10 mm. The unit of the increase in the number of water-stable aggregates of 3–1 mm corresponded to 0.01–0.02 ESP units which demonstrates their involvement in the formation of water-stable structure due to the formation of the most valuable aggregates. The calculations with the fraction of water-stable aggregates of 1–0.25 mm showed a strong correlation with the number of air-dried structural units: it is direct for structural units of 7–5 mm and inverse for the units of 3–1 and 0.5–3 mm. In the former case, the unit of the increase in the number of water-stable aggregates of the mentioned size corresponded to the increase in the units of 7–5 mm per 0.26 units, and in the latter – the number of structural units of 3–1 and 3–0.5 mm decreased by 0.46 and 1.15 units.

The inverse correlation was found between the number of water-stable aggregates of 1–0.25 mm and the number of ESP by size practically for all the fractions which demonstrated the involvement of ESP in water-stable fraction of the mentioned size. It was found that the units of the increase in the number of water-stable aggregates of 1–0.25 mm corresponded to the decrease in the number of ESP by 0.001–0.075 mm.

The most active involvement in water-stable aggregates was noted for ESP of 0.20 and 0.16 mm, and with the decrease in their size, the regression coefficients decreased 7.5–75 times with regard to the fraction of 0.20 mm which demonstrates the decrease in the soil-building activity of the fragments of soil-building type in the formation of water-stable aggregates.

As shown (Table 6), under the agrogenic load, the highest number of paired correlation coefficients, binding the block of water-stable structure, the block of air-dried structure, and the block of ESP was found in the soil object – *typical low-humus heavy-loamy light-clay chernozem on loess-like clay*. The calculated correlation coefficients demonstrated that water-stable aggregates of 3–1 mm correlated with the number of structural units of the most valuable fractions at the

Table 6. The regression equation and correlation coefficients for the dependence between the content of water-stable aggregates on the content of different fractions of structural units and ESP under postagrogenic maintenance and agrogenic load of soil types of the Forest-Steppe

Structural units, ESP, mm	Regression equation	Coefficients		Reliability p
		of correlation R ±	of determination, R^2	
Postagrogenic maintenance of chernozems – fallows and virgin soil *3-1 mm – water-stable aggregates*				
3–1	y = 7.18 + 0.56*x	0.65;	0.43	0.01
1–0.5	y = –4.65 + 0.41*x	0.65	0.43	0.01
0.5–0.25	y = 13.3–0.24*x	–0.55	0.30	0.02
0.125	y = –0.44 + 0.02*x	0.66	0.44	0.02
1–0.25 m – water-stable aggregates				
7–5	y = 4.02 + 0.26*x	0.65	0.42	0.01
3–1	y = 33.9–0.46*x	–0.61	0.37	0.03
0.5–3	y = 54.1–1.15*x	–0.65	0.43	0.01
0.20	y = 2.68–0.075*x	–0.65	0.42	0.02
0.16	y = 1.30–0.04*x	–0.59	0.35	0.02
0.125	y = 0.41–0.01*x	–0.55	0.30	0.02
0.10	y = 0.19–0.01*x	–0.55	0.30	0.05
0.071	y = 0.16–0.005*x	–0.61	0.37	0.03
0.05	y = 0.04–0.001*x	–0.55	0.30	0.05
<0.25	y = –0.38 + 0.46*x	0.55	0.30	0.05
Typical low-humus heavy-loamy light-clay chernozem on loess-like clay *3–1 mm – water-stable aggregates*				
5–3	y = 3.27 + 0.35*x	0.61	0.37	0.006
3–1	y = 7.43 + 0.49*x	0.67	0.45	0.001
1–0.25	y = 19.1–0.49*x	–0.65	0.43	0.002
0.071	y = –0.09 + 0.02*x	0.49	0.24	0.03
0.05	y = –0.016 + 0.003*x	0.50	0.25	0.03
1–0.25 mm – water-stable aggregates				
0.5–0.25	y = 2.19 + 0.30*x	0.45	0.21	0.04
1–0.25	y = –0.91 + 0.17*x	0.46	0.22	0.03
0.125	y = 2.63–0.05*x	–0.55	0.31	0.02
0.10	y = 2.83–0.06*x	–0.56	0.32	0.01
0.071	y = 1.22–0.03*x	–0.55	0.30	0.02
0.05	y = 0.14–0.004*x	–0.66	0.44	0.003

level of direct correlation, and the unit of the increase in the mentioned fraction of aggregates was the increase in the content of the most valuable structural units per 0.35–0.49 content units. Water-stable aggregates of 3–1 mm correlated with the content of structural units of 1–0.25 mm at the level of inverse correlation, and the increase in the content of water-stable aggregates (3–1 mm) decreased the content of the mentioned fraction of structural units by 0.49 units.

A water-stable fraction of 3–1 mm correlated with ESP with the fraction of (0.071–0.05 mm) at the level of weak direct correlation as compared with the postagrogenic maintenance of soil types. In meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay, the correlation between the fraction of water-stable aggregates of 3–1 mm was found with the most valuable structural units. The increase of water-stable aggregates ensured the increase in structural units by 0.29–0.39 which is less compared to the postagrogenic maintenance of chernozems. There is somewhat weaker inverse correlation between the mentioned fraction of water-stable aggregates with structural units of 1–0.5 mm and the regression coefficient as compared with postagrogenic maintenance of soil types. The increase in the content of the fraction of water-stable aggregates of 1–0.25 mm was related to the most valuable groups of structural units and correlated at the level of direct dependence. The regression coefficients for the increase in their number per unit ensured their increase by 0.17–0.20 units. The correlation between the fractions of water-stable aggregates of 3–1 mm and 1–0.25 mm was at the level of R < ± 0.3, which demonstrates a low level of ESP involvement in water-stable aggregates, and soil may be characterized as unstable with the poorer level of aggregation capability.

The soil type of *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay* was characterized by the low ability to structuring. The correlation coefficients between the fraction of water-stable aggregates of 3–1 mm and 1–0.25 mm were smaller than R < ± 0.50, and the relation to ESP was at the level of R < ± 0.3, which demonstrates a very weak manifestation of structure-formation as a manifestation of general soil-formation under agrogenic impact.

The ability of water-stable aggregates to submit to the formation of structural units of agronomically valuable size and to involve ESP in aggregation may be used to evaluate the stability of the hierarchy of structural state as a manifestation of soil-formation under agrogenic load on soil types in the Forest-Steppe. The most stable hierarchical system of the structural composition of soil types is formed under the postagrogenic maintenance of soils.

The most stable soil type is *typical low-humus heavy-loamy light-clay chernozem on loess-like clay*, where the number of direct and inverse correlations R > ± 0.5 does not deviate from the number under the post-agrogenic maintenance for more than 15 %, which ensures a high level of self-organization of the structural state.

Table 7. The parameters of evaluating the water stability of the structure and the level of agrogenesis manifestation in soil types under postagrogenic maintenance and agrogenic load for the Forest-Steppe conditions

Quantile rates	3–1 mm > 0.25 mm %	Weighted average diameter of aggregate, mm	**Fractal dimensionality, D	Index of Hurst, H	State of water stable structure	Manifestation of agrogenesis
L_{01}	8.00 55.5	0.70	1.77	0.23	extremely unstable	very weak
$L_{0.25}$	13.5 65.0	0.75	1.65	0.35	unstable	weak
$L_{0.5}$	20.0 70.0	1.25	1.48	0.52	medium stable	medium
$L_{0.75}$	30.0 75.0	1.77	1.01	0.79	stable	high
$L_{0.90}$	35.0 80.0	2.14	1.07	0.93	excessively stable	very high

Note. *$0.5 < H < 1.0$ – persistent or trend-stable rows, 2) $H = 0.5$ – index of Hurst indicates a random row, 3) $0 < H < 0.5$ – range, corresponding to antipersistent rows (“returning to the average”). **D = 1.01–1.40 – stable state; D = 1.40–1.60 – stability threshold; D > 1.69 – unstable state.

In case of a decrease in the number of correlations of $R > \pm 0.5$ level regarding postagrogenic maintenance *of chernozems down to* 30 % *(*soil type – *meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay*) and >50 % (*gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay*) there is a decrease in the level of hierarchical composition of the soil structure (Table 7).

The following soil parameters were selected to evaluate the state of the water-stable structure under the postagrogenic maintenance and agrogenic load: the weighted average diameter, the content of water-stable aggregates of 3–1 mm, >0.25 mm which are related to the main factor (F_1) by strong inverse correlation ($R = –0.80–0.96 \pm 0.03$); aggregates of 1–0.25 mm related to F_1 by direct correlation coefficient ($R= =+0.80 \pm 0.02$).

The evaluation parameters were fractal dimensionality (D) and the index of Hurst (H), as indices of the direction of water stability by trend characteristics of the distribution of aggregates. The relation to F_1 was at the level of strong inverse correlation by indices D and H. 80 % of total dispersion by F_1 and F_2 fell on the mentioned indices by dispersion regarding $F_{1,}$ which demonstrated the significance of the selected indices for the evaluation of water stability of the structure with the evaluation of agrogenesis manifestation.

The clusterization of the selected indices showed that at the level of 4–5 % there is the integration of D, H, and d, and further clusterization at 60 % occurs with the content of 3–1 mm and additionally with the fraction of 1–0.25 mm. It is reasonable to establish regression dependence with these fractions of water-stable aggregates and weighted average diameter of water-stable aggregates, d.

The correlation coefficients between the content of water stable fraction of 3–1 mm, 1–0.5 mm, >0.25 mm, d, mm and the indices of D, H, C were at the level of strong direct correlation ($R = +0.79–0.86 \pm 0.02$), and at the level of strong inverse correlation with D index and the content of water stable fraction of 1–0.25 mm.

The obtained dependence equations are as follows:

a) to determine the weighted average diameter, d, mm

d, mm (y): 3–1 mm: $y = 1.46 + 15.1{*}x$; $R = 0.86$;
d, mm (y): 1–0.25 mm: $y = 58.0–18.33{*}x$; $R = –0.89$;

b) to determine the fractal dimensionality, D:

D(y): 3–1 mm: $y = 74.3–36.4{*}x$; $R = –0.93$;
D(y): >0.25 mm: $y = 108.5–27.9{*}x$; $R = –0.83$;
D(y): 1–0.25 mm: $y = –12.2 + 31.9{*}x$; $R = 0.71$;
D(y): d, mm: $y = 4.20–1.99{*}x$; $R = –0.90$;

Note: $D = 1.01–1.40$ – stable state; $D = 1.40–1.60$ – stability threshold; $D > 1.69$ – unstable state.

c) to determine the index of Hurst, $H = 2–D$:

H(y):d, mm: $y = 0.21 + 1.99{*}x$; $R = 0.90$;
H(y): 3–1 mm: $y = 1.43 + 36.4{*}x$; $R = 0.94$;
H(y): >0.25 mm: $y = 52.7 + 27.9{*}x$; $R = 0.83$;
H(y): 1–0.25 mm: $y = 51.7–31.9{*}x$; $R = –0.71$;

Note: $0.5 < H < 1.0$ – persistent or trend-stable rows, 2) $H = 0.5$ – index of Hurst indicates a random row, 3) $0 < H < 0.5$ – range, corresponding to antipersistent rows (“returning to the average”).

d) to determine the correlation degree, $C=2^{2H–1}–1$:

C(y): d, mm: $y = 0.68 + 1.58{*}x$; $R = 0.84$;
C(y): 3–1 mm: $y = 11.8 + 23.8{*}x$; $R = 0.72$;
C(y): 1–0.25 mm: $y = 44.8–27.0{*}x$; $R = –0.70$;

The main index for the evaluation of the state of a water-stable structure and the degree of agrogenesis manifestation is the weighted average diameter of water-stable aggregates, d. The presented regression equations for the dependence of D, H on d allow for obtaining the water stability indices for the structure of soil types in the Forest-Steppe of Ukraine. We elaborated a scale for evaluating the water stability of the structure and direction of agrogenesis under different agrogenic loads and maintenance of soil types (Table 7). The basis of the presented gradation is the discreteness of the change in the content of the most valuable water-stable aggregates of 3–1 mm and >0.25 mm. They are typical for the main soil types, which are functionally related to indices d, D, H which allowed for creating the gradation of the state of the water-stable structure by fractal indices and determining the agrogenesis level of soil types.

Table 8 demonstrates the agrogenic impact of the introduction of fertilizers and tillage on soil types with the consideration of elaborated criteria for evaluating the state of soil water-stable structure and agrogenesis. The least stable soil type was found to be *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay*. The introduction of the increasing amount of fertilizers had little effect on the change on evaluation indices, and the state of the water structure was characterized as unstable under the weak manifestation of agrogenesis. By the indices, soil type of *meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay* ensured a stable state of the water-stable

Table 8. The values of fractal dimensionality as an indicator of the stability of the distribution of water-stable aggregates under the agrogenic load in the soils of the Forest-Steppe of Ukraine

Introduction of fertilizers	Content of aggregates, 3–1 >0.25 %	Fractal dimensionality, D, mm	Index of Hurst, *H=2–D	Autocorrelation between fractions of water-resistant aggregates	State of water-stable structure
Gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay					
$N_{65}P_{60}K_{70}$+1 Ha $CaCO_3$	13.5 69.9	0.75	1.58	0.42	unstable
$N_{90}P_{75}K_{85}$–1 Ha $CaCO_3$	9.53 64.4	0.70	1.62	0.38	unstable
Meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay					
$N_{100}P_{95}K_{90}$	21.2 65.3	1.04	1.44	0.56	stable
$N_{120}P_{110}K_{100}$	21.0 71.2	0.95	1.49	0.51	stable
Typical low-humus heavy-loamy light-clay chernozem on loess-like clay *Ploughing*					
$N_{90}P_{75}K_{90}$	7.80 55.7	0.92	1.69	0.31	unstable
$N_{120}P_{85}K_{115}$	8.0 57.7	0.75	1.77	0.23	very unstable
No-till					
$N_{90}P_{75}K_{90}$	15.1 65.0	1.13	1.61	0.45	unstable
$N_{120}P_{85}K_{115}$	17.9 67.8	1.40	1.47	0.55	stable
Typical high-humus medium-clay chernozem on loess-like clay					
Ploughing, 77 years	8.30 46.0	0.74	1.90	0.20	very unstable
Typical medium-humus heavy-loamy chernozem on loess					
Ploughing, 75 years	15.0 58.0	0.85	1.76	0.24	unstable
Subsurface, 25 years	18.1 65.0	1.09	1.60	0.45	unstable

Note. $0.5 < H < 1.0$ – persistent or trend-stable rows, 2) $H = 0.5$ – index of Hurst indicates a random row, 3) $0 < H < 0.5$ – range, corresponding to antipersistent rows (“returning to the average”).

structure and a medium level of agrogenesis due to high content of water-stable fraction of 3–1 mm, the content of which decreased after increasing the amount of fertilizers.

Under systematic ploughing, the soil type of *typical low-humus heavy-loamy light-clay chernozem on loess-like clay* affected the increasing dose of fertilizers which decreased the weighted average diameter of aggregates 1.48 times. In control without fertilizers, the value d corresponded to the stable state of a water-stable structure but the high level of d was formed due to the high content of the fraction of water-stable aggregates of 1–0.25 mm. However, under No-till system, the state of water-stable structure passes to the stable level which demonstrates high sensitivity of this soil type to the effect of direction and force of agrogenic load under agrogenesis. Under systematic ploughing, the soil types of *typical medium-humus heavy-clay chernozems on loess* become unstable by their state of the water-stable structure, and the effect of the soilprotective tillage is rather a sensitive agrogenic factor towards enhancing the water stability of aggregates and agrogenesis towards maintaining the fallow.

DISCUSSION OF STUDY FINDINGS

The international publications of the study results regarding the formation of the structural-aggregate state demonstrate great urgency of the issue of preserving and restoring the soil structure. However, the studies are mainly dedicated to the general investigation of the structural state in natural conditions in the general fundamental approach from the standpoint of classic soil science (Christensen, 2001; Emadodin et al, 2009; Soleimany et al, 2021; Manoj et al, 2020; An et al, 2008; Garcia-Oliva et al, 2004; Lu et al, 2014; Rohoskova and Valla, 2004; Sena et al, 2002). Thus, the presented results of the study of regularities in the formation of structural-aggregate state under agricultural use of soils as compared to the ones under fallow are valuable for the formation of the notion about the change in the aggregate state (Degtyarev and Panasenko, 2013).

The study of the water-stable structure is especially valuable (Medvedev, 2008). The structure of chernozem-type soils, optimal for the development of plants, may be stable to different moisturization conditions and ensure the consistency of maintaining the pores of the soil matrix, creating the favorable air- and moisture exchange regime between the roots and soil environment (Degtyarev et al, 2020). The water-stable aggregate structure is formed by macro- and microaggregates, and the water stability of aggregates is determined by the content of organic carbon in the aggregates and has a direct effect on the structural state of soil and its physical properties (Degtyarev et al, 2020; Demidenko et al, 2014; Medvedev et al, 2003). The decrease in humus composition and negative changes in soil absorption complex is one of the reasons for the unfavorable transformation of the structural state of arable chernozems – a phenomenon of common incidence (Medvedev, 2010; Sinchenko, 2019).

A common regularity in the formation of water stability of soil structure for chernozem-type soils, and to some degree for gray forest soils, was determined (Bulyhin et al, 2014; Bulyhin, 2020), the essence of which lies in the fact that if the number of microaggregates, involved in the formation of stable meso- and macroaggregates, exceeds 40 %, there are conditions for the restoration of the forfeited small lump-grain structure with a high level of water stability. The presence of a sufficient number of free- and loosely connected microaggregates ensures a high level of biological activity, the intensity of synthesis of newly-formed humic compounds and detritus, and the degree of saturation of physical clay with humus under different granulometric compositions of chernozem soils determines the direction of both humus accumulation and structure-formation in agrosystems.

Under intense tillage, the number of free- and loosely connected aggregates in the soil layer under tillage decreases down to 17–20 %, and at the background of the organic-mineral system of fertilization, the content of the mentioned groups of microaggregates increases up to 25 %, which is insufficient for the restoration of water stable structure in the former case, and ensures its inconsiderable restoration, in the latter. The decrease in technogenic load due to the use of minimal tillage and No-till system promotes the increase in the content of free- and loosely connected microaggregates up to 40 % and more, which ensures the restoration of water stable structure as early as years 5–7.

The enhanced microaggregation in preservation tillage technologies is explained by the fact that detritus and newly formed humic compounds enhance their role in the formation of organo-mineral complexes in case of optimization of hydrothermal conditions in the seasonal cycle and decreased tempo of humus mineralization. The correlation coefficient between the number of aggregates, sized 0.01–0.25 mm, and the content of peptized humic compounds during intense tillage was as follows: $R = +0.48 \pm 0.01$, and under soil restoring technologies: $R = +0.70–0.75 \pm 0.01$.

Under systematic minimalization of soil tillage, the water stability of soil structure in seasonal and annual cycles is subject to the cyclic character of the humus state. In spring, water-stable aggregates of 0.5–3 mm prevailed in the total of agronomically valuable aggregates, and closer to the end of the vegetation period, more aggregates of 0.25–0.5 mm and <0.25 mm were formed. In spring, under the sufficient introduction of organic and mineral fertilizers from autumn, the number of water-stable aggregates of 0.5–3 mm got restored to the initial level due to the newly-formed humus under simple restoration of fertility and increased under its extended restoration.

To evaluate the dependence between the moisturization factor and the degree of water stability of the structure, we calculated correlation coefficients between the field moisture (%) and the number of water-stable aggregates of 0.5–3 mm and 0.25–

0.5 mm. Under ploughing, the connection is at the level of strong correlation: R = +0.78 ± 0.09, and under preservation tillage, the connection gets weaker to the level of medium correlation: R = +0.50–0.55 ± 0.09. In the former case, the water stability of the structure depended on the moisturization level by 65 % and in the latter – by 30 %.

Further calculations demonstrated that the method of soil tillage affected the connection between the content of water-stable aggregates of > 0.25 mm and the content (t/ha) of humic compounds, capable of peptization. It turned out that under surface tillage, there was a stronger connection between the water stability degree and the content of humic compounds, capable of peptization: under ploughing, they determined water stability by 25 %, and under surface tillage – by 88 %.

The re-grouping of structural units within agronomically valuable intervals towards coarsening with the formation of units of 2–5 mm and water-stable aggregates of 0.5–3 mm, the weakening of the dependence of water stability of the structure on the degree of moisturization and subjugation of humus state in the seasonal and annual cycles, the change in water stability of chernozem structure is the manifestation of termination of agrophysical degradation and the restoration of this state after the refusal from ploughing is a criterion of decreased risks while transferring to continuous surface tillage and No-till system in the initial period of its implementation (Demydenko O, 2019; 2020).

CONCLUSIONS

The soil types of the Forest-Steppe form the distribution of water-stable aggregates within the agronomically valuable interval by the unified principle, forming “prevailing” sizes of aggregates in the size interval of 5–3 mm and 2–1 mm, but under the different quantitative level of humps of the maximal accumulation of aggregates which ensures the re-distribution state as persistent with the index of Hurst of H = 0.78–0.94. The agrogenic effect changes the re-distribution of water-stable aggregates depending on the granulometric composition but ensures the antipersistent state of the distribution with low stability (D = 1.41–1.65) and low level of correlation in the row of the distribution of the aggregate fractions.

Under the postagrogenic maintenance of soil types, there is a stable mutual connection between water-stable aggregates, structural units and ESP, and in the total of relations, direct and inverse correlation relations of R > ± 0.50 level are 33 % with the 1.3 to 1 ratio in favor of inverse proportion relations which ensures a high level of self-regulation for the hierarchical organization of the structural state. Under postagrogenic maintenance, the regularity is disrupted: the relation of R > ± 0.50 level decreases twice, which disrupts the self-regulation of the structural state. If the quantitative level of the relations of R > ± 0.50 level is preserved, the soils become sensitive to technogenic impacts as a soil type of *typical low-humus heavy-loamy light-clay chernozem on loess-like clay*.

The determining index, characterizing the stability level of the water-stable structure, was found to be the content of water-stable aggregates of 3–1 mm and >0.25 mm and the weighted average diameter of water-stable aggregates of the agronomically valuable interval of sizes that demonstrated a strong correlation (R = = ±0.76–0.96 ± 0.02) with fractal dimensionality (D) and the index of Hurst (H) which allowed for forming a gradation scale for the evaluation of the state of water-stable structure and the degree of manifestation of agrogenesis of chernozems in the Left-Bank Forest-Steppe under the different introduction of fertilizers and soil tillage. It was found that by the rate of agrogenesis manifestation via the formation of the degree of the water-stable structure, the soils of chernozem type were divided as follows: *gray forest low-humus heavy-loamy light-clay soil on carbonate loess-like clay < typical low-humus heavy-loamy light-clay chernozem on loess-like clay < meadow-chernozem low-humus carbonate heavy-loamy soil on loess-like clay < typical medium-humus heavy-clay chernozem on loess.*

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Стан водостійкої структури ґрунтів Центрального Лісостепу за агрогенного і постагрогенного використання

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Мета. Встановити закономірності формування водостійкої структури та отримати об'єктивну цілісну інформацію про процес розпаду та консолідацію водостійкої структури за агрогенного і постагрогенного навантаження на основні ґрунтові відміни Центрального Лісостепу України. **Методи.** Польовий – досліджувалися ґрунти чорноземного типу (7 грунтових відмін чорноземного типу різного гранулометричного складу та гумусованості) центральної частини Лісостепу України, лабораторно-аналітичний (проведення мокрого розсіювання ґрунтової структури), математично-статистичний (метод непараметричної статистики, факторний, кластерний та фрактальний аналізи). **Результати.** Аналіз вивчення стану водостійкості структури ґрунтів чорноземного типу в Лісостепу свідчить про перспективність застосування сучасних статистичних методів: фрактального, факторного, кластерного та методу непараметричної статистики, що виявляє їхню чутливість до незначних змін у розподілі водостійких агрегатів у межах агрономічно цінного інтервалу. Ґрунтові відміни постагрогенного утримання формують розподіл водостійких агрегатів, утворюючи «переважаючі» розміри агрегатів в інтервалі розмірів 5–3 та 2–1 мм, що забезпечує персистентний стан перерозподілу, де показник Херста набуває значень $H > 0{,}75$. Агрогенний вплив на ґрунти змінює перерозподіл водостійких агрегатів, руйнуючи їхній природний розподіл, забезпечуючи антиперсистентний стан розподілу з низькою стійкістю ($D > 1{,}43$ та $H < 0{,}58$). За постагрогенного утримання ґрунтових відмін формується стійкий взаємозв'язок між водостійкими агрегатами, структурними окремостями та ЕГЧ ($R = +0{,}78$), а з усієї сукупності кореляційних зв'язків, на зв'язки прямої і оберненої $R > \pm 0{,}55$ приходиться >30 % із співвідношенням 1,5 до 1 на користь обернених зв'язків, що забезпечує високий рівень саморегуляції ієрархічної організації структурного та водостійкого стану. **Висновки.** Детермінувальним показником, який характеризує рівень стійкості водостійкої структури, виявився вміст водостійких агрегатів 3–1 і >0,25 мм та середньозважений діаметр водостійких агрегатів агрономічно цінного інтервалу розмірів, з якими встановлено тісний кореляційний зв'язок ($R = \pm 0{,}76–0{,}96 \pm \pm 0{,}02$) з фрактальною розмірністю ($D > 1{,}4$) та показником Херста ($H < 0{,}5$), що дало можливість розробити градаційну шкалу оцінки стану водостійкої структури і рівня прояву агрогенезу ґрунтів Лісостепу України. За рівнем прояву агрогенезу через формування рівня водостійкої структури ґрунти чорноземного типу розподілилися: *сірий лісовий малогумусний крупнопилувато-легкосуглинковий на карбонатному лесоподібному суглинку < чорнозем типовий малогумусний крупнопилувато-легкосуглинковий на лесоподібному суглинку < лучно-чорноземний малогумусний карбонатний крупнопилуватий на лесоподібному суглинку<чорнозем типовий середньоґумусний важкосуглинковий на лесі.*

Ключові слова: водостійкі агрегати, агрономічно цінний інтервал, фрактальна розмірність, середньозважений діаметр, агрогенез, водостійкість, ЕГЧ.

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