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Research on the Agrophysical State of Podzolized Black Soil under Different Transitions to "No-Till" Treatment in Agrocenosis

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ABSTRACT

The performance of the No-till treatment after systematic surface tillage with crop rotation allowed the formation of stocks of productive moisture at the average level of 155 mm, which corresponded to the stocks of moisture after ploughing and were significantly higher (by 10–15 mm) than those under systematic surface tillage and No-till treatment after the ploughing. During the April-June and June-July periods, ploughing consumed 67% and 33% of the spring moisture supply, respectively; after surface tillage it was 62% and 38%, while after No-till following surface tillage it was 55% and 45%. This indicates a more optimal use of productive moisture stocks compared to ploughing, where moisture was used 1.2 times more intensively during the vegetative growth phase of grain and leguminous crops in the crop rotation. The highest consumption of productive water stocks during the April-July period was during ploughing at 62–69 mm and during surface tillage and No-till after surface tillage at 47–48 mm, which is 1.4 times less. The content of water-resistant aggregates 5–1 mm in 0–30 cm layer of soil under tillage was 3.31%, whereas under surface tillage and No-till treatment in different combinations – 1.87–2.21 times more. Increasing the content of water-resistant aggregates of the most valuable size, with increasing of humus content in 0–20 cm layer of soil by 0.07% under surface tillage and No-till treatment on its background led to improvement of crop moisture regime in agrocenosis by 10–15%.

Keywords: agrophysical degradation, water resistance, no-till treatment, ploughing, productive moisture, structural density.

INTRODUCTION

The main objective of introducing no-till farming in the forest-steppe is to reduce energy, money and time expenditure, primarily by reducing the number and depth of tillage operations, but also by combining several operations in one technological process. In recent decades in Ukraine, as a result of the decline in agriculture, there has been a spontaneous minimisation of black soil cultivation, which has nothing to do with scientifically based zonal minimisation [Medvedev et al., 2017; Medvedev, 2014]. In addition, there is a general trend in the world, as well as in Ukraine, to reduce the intensity of tillage, not only to save material and energy resources, but also due to the general trend of a declining labour force in rural areas. The latter contributes to a reduction in the technological cycle of work by using more productive wide-shaft machine units to increase labour productivity in agriculture, provided in particular by minimum and No-till treatment technologies [Derpsch, 2008; Shikula & Demidenko, 2004; Shikula & Demidenko, 2005; Kiryushin, 2006], which is also relevant in wartime economic conditions. Minimising tillage in agrocenoses is advisable on soils with an equilibrium density close to optimal for growing field crops; on these black soils, the intensity of tillage can be reduced and some techniques can be abandoned altogether [Kosolap & Krotinov, 2011].

The global trend towards minimal tillage is driven not only by an attempt to reduce material and labour expenses, but also by the possibility of managing the soil-formation process [Shikula & Demidenko, 2004; Shikula & Demidenko, 2005] with access to extended soil fertility reproduction, which is unrealistic with constant ploughing in agrocenoses [Medvedev, 2010; Thorne et al., 2003; Tiscareño-López et al., 2004]. Minimum tillage of black soils ensures sustainable yields in agrocenoses under conditions of increased doses of organic and mineral fertilisers and effective plant protection products. The longer systematic minimum tillage is applied, the higher the fertility of the black soil and the crop yields [Shikula & Demidenko, 2005; Rodrigo et al., 2021].

In recent decades, losses of soil organic carbon (SOC) have increased significantly due to the expansion of the agricultural area under crops. Besides, the intensification of tillage resulted in a significant reduction of the initial SOC stocks in the fields in the 0–30 cm and 0–100 cm soil layers by 26% and 16% respectively, affecting, above all, the agrophysical soil conditions in agrocenoses [Sanderman et al., 2017]. The loss of organic carbon reduces soil quality and, as a consequence, contributes to climate change by increasing the amount of CO^2 in the atmosphere [Lal, 2010]. One way to preserve agricultural soil fertility is to switch to conservation tillage No-till (NT). No-tillage (NT) farming should be a major component of conservation agriculture, as it is carried out with minimal soil disturbance [Nunes et al., 2020].

The issue of the properties of NT soils that promote carbon sequestration is also important. Some findings suggest that there is little or no difference in SOC content between ploughed and NT soils when soil samples are taken deeper than 30 cm [Angers & Eriksen-Hamel, 2008; Baker et al., 2007]. At the same time, the introduction of NT treatments leads to an accumulation of soil organic carbon (SOC) in the surface soil layers as well as an increase of microbial biomass [Dietzel et al., 2017; Wuaden et al., 2020]. Several studies indicate that this effect is sometimes partially or completely offset by the higher SOC content in the lower part of the tilled soil layer when ploughing [Melero et al., 2009].

The relevance of the study under consideration is that in order to save resources and obtain consistently high crop yields in agrocenoses, it is necessary to focus on the development of improved ways of transition to growing crops using the No-till treatment. At the same time, a high agrophysical potential of black soil should be developed in the transition period after abandoning ploughing, thus increasing the efforts to improve the agrophysical condition of black soil to ensure a stable yield for the first years of No-till application.

The study aims to substantiate scientifically the expediency of different periods of transition from ploughing to No-till treatment and determine its influence on the change of agrophysical conditions of fertility as a basis for optimization of moisture regime of podzolic strongly degraded low humus black soil in 5-field grain crop rotation for conditions of Central Forest-steppe of Ukraine.

MATERIALS AND RESEARCH METHODS

The research was conducted in a stationary field experiment at the Cherkaskiy State Agricultural Experimental Station of the NSC "Institute of Farming with the National Academy of Sciences" in 2016–2022. Soil – podzolised strongly graded low-humus medium-loam on carbonate mole loess 49°11′13″ north latitude, 31°51′58″ east longitude. The humus content of the cultivated soil layer – 2.76–3.03% under I.V. Tyurin, sum of absorbed bases – 24.5–28.1 mg-eq per 100 g soil, hydrolytic acidity – 1.99–2.19 mg-eq·(100 g soil)$^{-1}$, pH salt extract – 5.56–6.31. Degree of base saturation 92.8–93.3%, content of mobile forms of phosphorus (according to Truog) – 9.0 mg per

100 g soil, exchangeable potassium (according to Brovkina) – 12 mg per 100 g soil.

The research was carried out in a field experiment to study the productivity of a 5-field grain-tillage crop rotation, which included: peas, winter wheat, soy beans, winter wheat, barley (up to 60% – cereals; 20% – legumes; 20% – soy beans). Fertiliser system $N_{75}P_{65}K_{82}$ + 6–7 t·ha^{-1} by-products. The tillage system included 4 variants:

1) ploughing at 22–25 cm in crop rotation (for winter wheat – treatment – at 8–10 cm);
2) no-till treatment after minimal treatment, following systematic ploughing at 22–25 cm to level the field surface;
3) no-till treatment according to the 6-year background of surface tillage;
4) surface soil treatment at 10–12 cm in the course of 7 years.

Soil sample analyses, counts, and calculations were conducted in accordance with special methods:

1) field humidity – by thermogravimetric method during the main periods of cultivation (PST ISO 11465:2001) to 100 cm depth; moisture stocks – based on calculations to 100 cm depth.
2) stacking density – by the method of cutting rings according to N.A. Kachinsky's modification in the periods of intensive crop growth and in the periods of crop formation (PSTU ISO 11272:2001) to 30 cm depth along soil layers of 0–10 cm, 10–20 cm, 20–30 cm;
3) structural and aggregate composition by the sieve method modified by N. I. Savinov (GOST 4744:2007) and water resistance according to the method of I. M. Baksheev in the layer 0–30 cm.
4) total humus content – according to I.V. Tyurin, modified by M.V. Simakov (GOST 4289:2004).

Structural density, stocks of productive moisture, determination of structural-aggregate state were determined under each crop in the crop rotation. Average values of agrophysical indicators were determined. The porosity coefficient by calculation: K_{pr} = TP:SF, where TP – total porosity; SF – solid phase. Statistical calculations of the research results were carried out by the "Method of analysis of variance" using the "STATISTICA" programme, using nonparametric statistical methods and fractal analysis.

RESEARCH RESULTS

Analysis of the structural condition of the soil during dry sowing in a 5-field crop rotation has shown that regardless of the tillage method, the content of agronomically valuable structural detritus (according to N.I. Savinov: 10–0.25 mm) was practically the same 80.1–84.5%, and according to I.B. Revutu (7.0–0.25 mm) made up: during ploughing – 67.8%, further with surface tillage and No-till systems – up to 70.7%, and under deposit conditions it reaches a value of – 84.5% and 71.0% (Table 1).

The ratio of 10–0.25 mm to 7–0.25 mm detritus content during ploughing and No-till after ploughing was 1.18 to 1, whereas with the No-till system, after surface tillage – 1.20 to 1, and at fallow – 1.19 to 1, i.e. close in value and characterises the stability of the soil structure of the

Table 1. Influence of tillage method and under-fallow content on the structural condition of podzolized black soil in a 5-field crop rotation

Method of treatment	Dry sowing, %				
	Size, mm			$\frac{K_{st1}}{K_{st2}}$	D, mm
	$\frac{10\text{-}0.25}{7\text{-}0.25}$	$\frac{>10+<0.25}{>7+<0.25}$	$\frac{5\text{-}1}{3\text{-}1}$		
Ploughing	$\frac{80.1}{67.8}$	$\frac{19.9}{32.2}$	$\frac{50.7}{34.9}$	$\frac{4.01}{2.11}$	4.52
No-till after ploughing	$\frac{83.1}{70.7}$	$\frac{16.9}{29.3}$	$\frac{53.2}{35.8}$	$\frac{4.90}{2.41}$	4.45
Surface tillage	$\frac{81.6}{69.8}$	$\frac{18.4}{30.2}$	$\frac{52.4}{35.9}$	$\frac{4.10}{2.31}$	4.41
No-till after surface tillage	$\frac{81.9}{68.3}$	$\frac{18.3}{31.9}$	$\frac{50.4}{32.4}$	$\frac{4.47}{2.14}$	4.73
Deposits	$\frac{84.5}{71.0}$	$\frac{15.5}{29.0}$	$\frac{50.5}{27.5}$	$\frac{5.45}{2.45}$	4.59

Note: K_{st1} – the structure factor at the interval of agronomically valuable detritus 10–0.25 mm; K_{st2} – the structure coefficient for the interval of agronomically valuable parts 7–0.25 mm; D, mm – geometric mean diameter of the structural parts.

podzolized black soil The greatest amount of non-valuable aggregates (>10 + <0.25 mm) was during ploughing, and their amount had a steady tendency to decrease with the content of deposits – by 1.3 times. At the interval of valuable particles 7–0.25 mm, the content of non-valuable aggregates was in the range of 29.0–32.2%, and the ratio of groups of non-valuable particles was 0.6 to 1, while for contained deposits – 0.5 to 1. Regardless of the processing methods, the black soil part of 3–0.5 mm individual pieces in a total of 5–0.5 mm is 61–69%, and in deposits – 35%.

The coefficient of structure (K_{st}) in the agronomically valuable interval of 10–0.25 mm-sized detritus was the lowest during ploughing, while during surface and No-till treatment it increased by 1.11–1.22 times, and by 1.35 times when the deposits were contained. In the interval of valuable aggregates 7–0.25 mm K_{st} relative to ploughing, it increased by 1.10–1.16 times and the average weighted diameter of the structural units was changed from 4.41 mm to 4.59 mm (Table 1). According to the above agrophysical indicators, there is a steady tendency to improve the structural condition of the 0–30 cm layer of black soil with surface tillage and the No-till.

Evaluation of the redistribution of structural parts within the agronomically valuable interval most clearly describes the structural state in the tillable soil layer (Fig. 1). Thus, the grouping of structural parts by size 7–5 mm, 5–3 mm, 3–0.5 mm, 0.5–0.25 mm and <0.25 mm allows to reveal general patterns of distribution. In the conditions of the deposits, two separate peaks are formed: up to 32% (7–5 mm) and about 26% (3–0.5 mm), and the content of particles with a size of 5–3 mm was about 22%. Under the influence of various methods of soil treatment, the general nature of the redistribution in groups of individual items is preserved, but with certain constrictions of the redistribution within the agronomically valuable interval. During ploughing, the content of particles 7–5 mm in size decreases to 24% and the content of particles 3–0.5 mm increases up to 34%, while the content of particles 0.5–0.25 mm increases as well. With surface and No-till treatment, after ploughing and surface loosening, there is a regrouping of particles in the direction of their content in deposits: the content of particles 7–5 mm in size increases to 27%, and that of particles 3–0.5 mm – to 32%, which is about 5 % for 7 years.

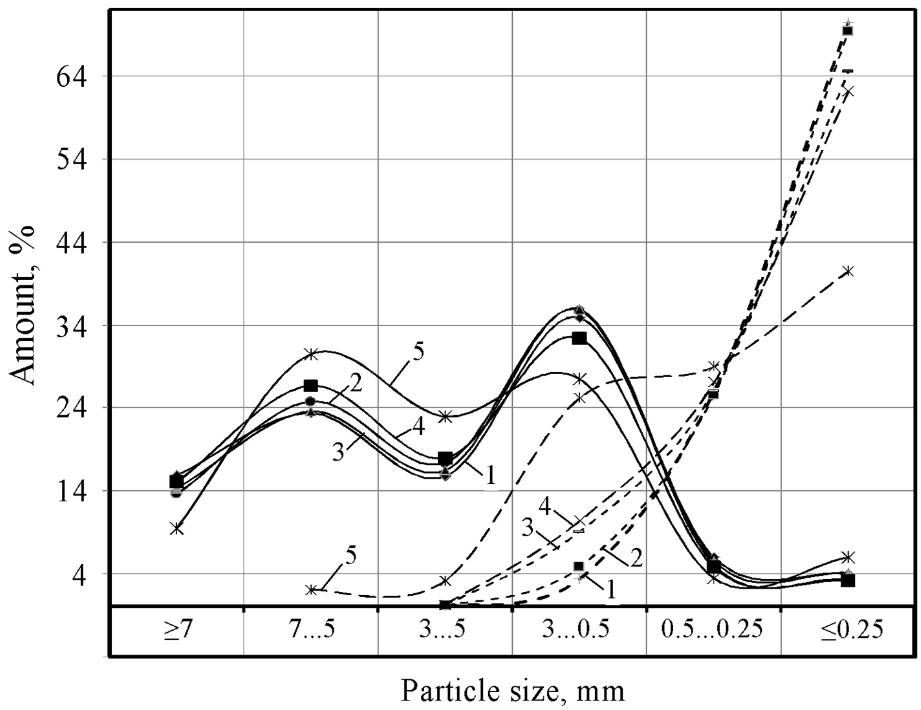

Fig. 1. Dependences of various methods of processing and the content of podzolized black soil on the redistribution of structural parts and water-resistant aggregates in a 5-field crop rotation in the spring period (0–30 cm): solid lines – dry sowing:1 – ploughing; 2 – No-till after ploughing; 3 – surface tillage; 4 – No-till after surface tillage; 5 – deposits; dashed lines – moisture sowing: 1 – ploughing; 2 – No-till after ploughing; 3 – surface tillage; 4 – No-till after surface tillage; 5 – deposits

Fractal assessment of the redistribution of structural elements in various processing systems and deposits showed that the fractal dimension, regardless of the treatment method, was within 1 < D < 1.5 or D = 1.32–1.34, that corresponds to a persistent state that will be preserved in the future. In case of contents, there is an indicator D = 1.22, which corresponds to the steady state (Table 2).

The given fractal analysis testifies to the high resistance of the structural state of the soil to destruction under the influence of various treatment systems, but compared to the content of the deposits, the structural content of the treated layer of black soil is characterized by significant destruction and the manifestation of degradation processes, which weaken under the influence of the surface tillage of the No-till system.

Evaluation of the waterproof structure of the soil showed that for water-resistant aggregates > 0.25 mm the largest amount was with ploughing (30.6%), while with surface and No-till treatment, after the surface one, the content of valuable water-resistant aggregates increased to 3.4% and 6.0%, and with contained deposits – to 29% (Fig. 1, Table 3).

Water-resistant aggregates with a size <0.25 mm in deposits were 40.5%, while their quantity increased to 28.9% during ploughing, during surface tillage – to 25.5%, and with No-till after surface loosening – to 22.9%, which is less compared to ploughing by 1.13 and 1.3 times, respectively. The content of water-resistant soil aggregates 5–1 mm during ploughing was 3.31%, whereas during surface and No-till treatment in various combinations – by 1.87–2.21 times, and with contained deposits – by 4.6 times more. The content of water-resistant soil aggregates with a size of 3–0.5 mm during ploughing was 1.9%, while with surface tillage their content increased by 1.38 times, and with the No-till – 1.19–1.25 times. However, relative to the content of fractions of aggregates 3–0.5 mm in the content of deposits, it was 8.3 and 5.99–6.90 times less in ploughing and soil protection treatments of the soil (Table 3).

The content of fractions of water-resistant soil aggregates 1–0.25 mm during ploughing was 28.7%, while with surface tillage and the No-till system, after surface loosening, their amount increased to 1.2–3.6%, and in deposits – to 15.1%.

Table 2. Fractal assessment of the distribution of structural elements of podzolic black soil depending on the method of treatment in a 5-field crop rotation

Method of treatment	Equation dependences, $Y = e^{bx}$	Fractal dimensions, D = 1–|±bx|	Hearst indicator, H = 2-D	Soil structure state
Ploughing	$Y = 35.4^{-0.34x}$	1.34	0.66	Unsustainable persistent
No-till after ploughing	$Y = 31.8e^{-0.32x}$	1.32	0.68	
Surface tillage	$Y = 29.6^{-0.28x}$	1.28	0.72	
No-till After surface tillage	$Y = 35.4e^{-0.36x}$	1.36	0.64	
Deposits	$Y = 22.3e^{-0.22x}$	1.22	0.78	

Table 3. Influence of the method of treatment and the content of deposits on the water resistance structure of podzolized black soil in a 5-field crop rotation

Method of treatment	Moisture sowing,%				
	Size, mm			*K	D, mm
	>0.25 <0.25	5-1 3–0.5	1–0.25 0.5-0.25		
Ploughing	30.6 69.4	3.31 1.90	28.7 27.1	46.0	0.30
No-till after ploughing	31.5 68.5	6.22 2.38	29.1 25.1	41.0	0.33
Surface tillage	34.0 66.0	7.30 2.62	31.4 26.5	33.0	0.37
No-till after surface tillage	36.6 63.4	7.00 2.27	34.3 29.3	32.0	0.38
Deposits	59.5 40.5	15.2 15.7	43.8 29.0	15.0	0.65

Note: *K – water resistance criterion, %; D, mm – geometric mean diameter of water-resistant aggregates.

At the same time, the content of fractions of aggregates with a size of 0.5–0.25 mm, regardless of the method of processing and the content of black soil, podzolized to 25.1–29.0%, and tended to increase with surface and No-till treatment after surface loosening.

Assessment of the water resistance criterion (K_{wr}) showed, that with surface and No-till treatment it decreases by 1.12–1.41 times, while with deposit content – by 3.1 times. At the same time, the weighted average diameter (D) of water-resistant aggregates varied inversely with K_{wr}: relative to ploughing, D increased by 1.10–1.26 times, and by deposits – by 2.17 times (Table 3).

This phenomenon can be explained by studying the nature of the redistribution of water-resistant aggregates within the value interval. It turned out that with surface and No-till treatment, water-resistant aggregates in the size range of 5–0.5 mm were aggregated and the content of water-resistant aggregates <0.25 mm in size decreased by 5% (Fig. 1). That is, for the determination of K_{wr} from fractions 1–0.25 mm, the aggregates moved into the size range of water-resistant aggregates >1 mm, which affected the value of K_{wr}, but at the same time, the value D increased. This indicates the incorrectness of such an indicator as an assessment (criterion) of the water resistance structure of podzolized black soil.

The use of surface tillage for 7 years and the implementation of the No-till treatment on it improves the structural-aggregate state of the podzolized black soil in the direction of the deposit content, and with systematic ploughing and the No-till treatment, after ploughing, a lower level of the structural-aggregate state is ensured, which, in its turn, ensures different qualitative state of the soil structure at its different quantitative state.

Fractal assessment of the distribution of water-resistant soil aggregates showed that indicator D was within the limits $1.5 < D \leq 2.0$ ($0 \leq H < 0.5$), characterizing the distribution of aggregates as anti-persistent, and a number of distributions of water-resistant aggregates – volatile. When deposits are contained, the distribution of aggregates according to indicators D and H decreases the volatility of the distribution, and the stability of the distribution of water-resistant aggregates increases. In the case of contained deposits, the distribution of aggregates according to indicators D and H, the volatility of the distribution decreases, and the stability of the distribution of water-resistant aggregates increases.

The determination of the density of compounds in the 0–30 cm layer of podzolic black soil showed that in the spring, in the conditions of a sharp transition during ploughing, the density of compounds in the average crop in the crop rotation was at the level 1.02–1.14 g·cm^{-3}, that ensured the overall porosity – 55.5–61.5% and ratio of pore volume with moisture to aeration pore volume 0.60–0.75 to 1. At the level of K_s = 1.17–1.29. No-till treatment after ploughing realized after plowing provided stacking density interval 1.06–1.13 g·cm^{-3}, overall porosity 57–59%, K_p = 1.25–1.35 and a ratio of pore categories 0.60–0.70 up to 1 in favour of pores with air (Table 4).

Performing surface tillage for 7 years has formed a density interval 1.09–1.19 g·cm^{-3}, total porosity 54–59%, K_p = 1.18–1.44 and the ratio of pore categories to moisture and air 0.65–0.85 to 1 in favour of pore volume with air. With No-till treatment after surface tillage the density interval was 1.15–1.22 g·cm^{-3} with overall porosity 53–56%, K_p = 1.13–1.27 and pore category ration 0.85–0.98 to 1, which is the most optimal and is ensured by the level of water resistance of the structure in the 0-30 cm layer of podzolised black soil (Table 4).

The density of the podzolic black soil structure during ploughing had a coefficient of variation of 7.63%, with the No-till treatment after ploughing, surface tillage and No-till treatment after surface tillage the coefficient of variation decreased by 1.2–1.64 times. Total porosity under surface tillage, No-till treatment after ploughing and surface tillage relative to porosity under ploughing tended to reduce the variability index by a factor of 1.50 and 2.57–3.87. The porosity and surface loosening coefficient was characterised by a lower coefficient of variation relative to ploughing of 1.25–1.36 times.

Calculation of the differential porosity showed that reducing the intensity of cultivation of black soil by systematically performing surface tillage followed by switching to the No-till treatment provides an increase in the volume of solid phase relative to ploughing by 5 vol.%. The capillary water volume reaches 18% and the aeration pore volume is 29.8 vol.%, which is 2.9 to 7.5 vol.% less than under ploughing, and the moisture/air pore volume ratio is 0.9 : 1, whereas under ploughing it is close to 0.6 : 1, which is 1.5 times more effective. It should be noted that an increase in the volume of soil solids increases the volume of pores with inaccessible and loose moisture by

Table 4. Standardised parameters of the agro-physical state of the podzolised black soil depending on the method of cultivation in a 5-field crop rotation

Parameters	Average	Median	Min	Max	Meaning of the quantiles $L_{0.25}$	Meaning of the quantiles $L_{0.75}$	*Coef. Var, %
			Amplitude range: (Δ_a = max – min)		Standardized range: $\Delta_{50\%} = L_{0.75} - L_{0.25}$		
Ploughing at 22–25 cm							
Stacking density, g·cm⁻³	1.08	1.07	0.92	1.23	1.02	1.14	7.63
Overall porosity, %	56.6	59.0	42.0	65.0	55.5	61.5	15.0
Pores with moisture: aeration pores	0.7: 1	0.6: 1	0.4: 1	0.9: 1	0.6: 1	0.8: 1	19.7
Porosity coefficient, K	1.43	1.45	1.13	1.85	1.29	1.56	12.9
No-till treatment after ploughing							
Stacking density, g·cm⁻³	1.10	1.12	0.97	1.18	1.06	1.13	5.48
Overall porosity, %	57.2	58.0	45.0	63.0	57.0	59.0	9.94
Pores with moisture: aeration pores	0.67: 1	0.7: 1	0.4: 1	0.8: 1	0.6: 1	0.7: 1	16.4
Porosity coefficient, K	1.40	1.34	1.22	1.70	1.33	1.45	10.3
Surface tillage at 10–12 cm for 7 years							
Stacking density, g·cm⁻³	1.12	1.12	0.95	1.24	1.09	1.19	6.84
Overall porosity, %	57.2	57.0	53.0	64.0	54.0	59.0	5.83
Porosity coefficient	0.67: 1	0.6: 1	0.4: 1	0.9: 1	0.65: 1	0.85: 1	24.3
Porosity coefficient, K	1.36	1.34	1.13	1.78	1.18	1.44	13.2
No-till treatment after surface tillage for 7 years							
Stacking density, g·cm⁻³	1.18	1.19	1.02	1.24	1.15	1.22	4.63
Overall porosity, %	54.9	54.0	52.0	61.0	53.0	56.0	3.87
Pores with moisture: aeration pores	0.86: 1	0.90: 1	0.40: 1	1.10: 1	0.80: 1	0.98: 1	18.1
Porosity coefficient, K	1.22	1.17	1.08	1.56	1.13	1.27	9.47

Note: *Coef. Var, % – variation coefficient, %.

1.1 times or 9.0%, which does not affect the optimality of the ratio between the volume of pore categories with moisture and air (Fig. 2).

Determination of structural density and calculation of differential porosity in June showed that the soil compaction density at surface tillage and No-till treatment was on the border of equilibrium density for podzolic black soils (1.27–1.30 g·cm⁻³), whereas at ploughing and No-till treatment it was in the more optimal range of values after ploughing (1.25–1.26 g·cm⁻³). The total pore-to-pore ratio exceeded 50% regardless of the tillage method, and the ratio of pore categories with moisture and air was the least optimal with ploughing (0.4 to 1), whereas with surface tillage and No-till the ratio was 0.51–0.54 to 1. (Table 5).

Determinations of agro-physical indices in July at the ripening period of spring and winter cereals showed that the stacking density during ploughing in the crop rotation was at 1.29 g•cm⁻³, and with No-till after surface tillage it was higher by 0.03 g•cm⁻³. On the other cultivation variants, the stacking density was within the equilibrium range. The total yield only with the No-till treatment after surface tillage was less than 50%. The ratio of pore categories with moisture and air at surface tillage and No-till treatment was more optimal 0.65 to 1 and 0.68–0.72 to 1, whereas at ploughing it was 0.52 to 1, which indicates the positive effect of surface tillage and No-till treatment on optimization of agrophysical properties of podzolized black soil in the rotation, which brings the soil into equilibrium and ensures more effective use of productive moisture during the vegetation period of the crop rotation (Table 5).

The total humus content of the 0–30 cm layer of podzolized black soil was determined in spring. On average, the humus content in the 0–20 cm layer of the soil in the rotation with systematic surface tillage was higher by 0.07%, which is significantly higher compared to the ploughing. In the 20–30 cm soil layer, the pattern is reversed.

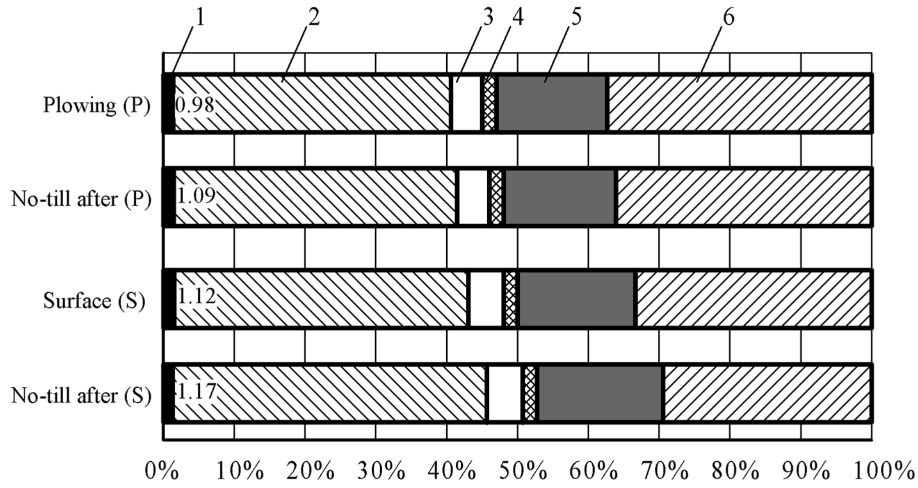

Fig. 2. Effect of different tillage systems on podzolic black soil on the differential water content in 0–30 cm layer of soil in the crop rotation: 1 – stacking density, g•cm^{-3}; 2 – soil solid phase, vol.%; 3 – firmly bound moisture, vol.%; 4 – loosely bound moisture, vol.%; 5 – capillary moisture, vol.%; 6 – aeration pore volume, vol.%

Table 5. Effect of different tillage systems of podzolic black soil on the differential water content in the 0–30 cm layer in the crop rotation

Density, g·cm^{-3}	Solid phase	Overall porosity	Pores: With moisture (A)	Pores: aerated (B)	A to B	*K
	об%					
June (lowering stage)						
Surface tillage						
1.27	49.0	51.0	17.9	33.1	0.54 : 1	1.05
No-till before surface tillage 6 years						
1.29	49.5	50.5	17.0	33.5	0.51 : 1	1.02
Systemic ploughing						
1.25	48.0	52.0	15.0	37.6	0.40 : 1	1.07
No-till after plowing						
1.26	48.0	52.0	17.0	35.0	0.49 : 1	1.07
July (the ripening phase of cereals and legumes)						
Surface tillage						
1.28	49.0	51.0	19.9	31.1	0.65: 1	1.04
No-till before surface tillage 6 years						
1.32	51.0	49.0	20.5	28.5	0.72: 1	0.96
Systemic ploughing						
1.29	49.0	51.0	18.0	33.0	0.55: 1	1.04
No-till after tillage						
1.29	49.0	51.0	20.4	30.6	0.68: 1	1.04

Note: *K – porosity coefficient.

Ploughing had the highest total humus content, while surface tillage had a lower content of 0.03%, which is significantly lower. The average humus content in the 0–30 cm layer of podzolised black soil was within a non-significant difference of 2.83–2.85%. In the case of deposits, the content of total humus in the 0–20 cm soil layer was 30% higher compared to the tillage variants. Similarly, in the 20–30 cm layer the humus content was 29–30% higher and overall in the 0–30 cm layer the humus content was 1.23–1.19% higher. A similar pattern was observed for humus

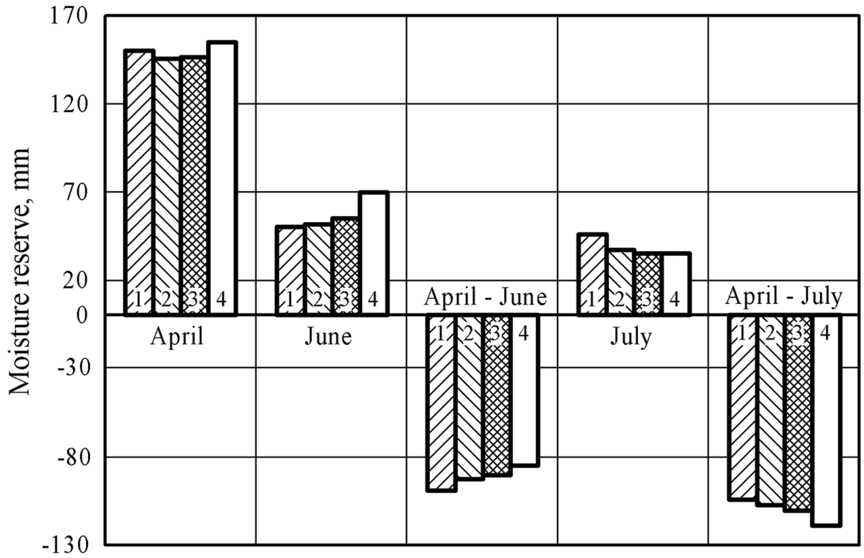

Fig. 3. Influence of different methods of cultivation of podzolic black soil on dynamics of storage and consumption of productive moisture in crop rotation in year 7 of the study

stocks. On average, the surface cultivation in the 0–20 cm layer increased the humus content by 5 t•ha^{-1}, and with minimum tillage after ploughing – by 3 t•ha^{-1}. In the 20–30 cm soil layer, humus reserves were within 30–32 t•ha^{-1} with an upward trend with minimal treatment. In general, high humus reserves in the 0–30 cm soil layer were with systematic surface tillage. With the deposit content, the humus reserves in the 0–20 cm soil layer were 85 t•ha^{-1}, 20–30 cm – 40 t•ha^{-1}, and in general in the layer 0–30 cm – 125 t•ha^{-1}, which is higher than ploughing by 25%, with minimum tillage – by 26% and by 24% higher, compared to systematic surface treatment.

Increasing the content of water-resistant aggregates of the most valuable size (3–0.5 mm) while improving the humus condition of podzolic black soil under surface tillage and No-till treatment in its background provides improvement of the soil moisture regime of crops in the agrocenosis. Determination of productive moisture reserves in the spring period in the 5-field crop rotation, depending on the method and system of cultivation of black soil, showed that with systematic ploughing, an average of 151 mm of productive moisture was accumulated in the one metre layer of soil. Moisture stocks under winter wheat and soybean crops were 147–148 mm and higher stocks under spring wheat and spring barley crops were 152 mm. On average, the ratio of productive moisture stocks in 0-50 cm to 50–100 cm thickness was 0.9: 1, which indicates a stable tendency for moisture dissipation in one-meter thickness of black soil (Fig. 3).

After soybean and spring wheat, the moisture ratio in the above soil strata was 1.0–1.1 : 1, indicating saturation with moisture evenly over the entire metre-long thickness. When performing the No-till treatment after ploughing, the average productive moisture stocks in the rotation were 148 mm with a 0–50 cm to 50–100 cm layer ratio of 0.94 : 1. High stocks of productive moisture were found under pea and soybean crops – 156-159 mm with a moisture stock ratio in the above layers of 0.92–0.96 : 1. Under winter wheat, spring wheat and spring barley crops, the moisture content in the layer thickness was 140–144 mm with a layer-to-layer ratio of 0.86–0.97 : 1. Under No-till treatment after ploughing compared to systematic ploughing, the formation of productive moisture stocks occurred with a significant deviation from the average value: up to 5% downwards in stocks and 7% upwards, which is much wider compared to systematic ploughing. The high stocks of productive moisture in spring under No-till treatment after surface tillage (+5 –10 mm), are due to an improved water-resistant structure, which determines better water permeability and the presence of a layer of vegetative mulch on the soil surface, contributing to snow accumulation and less frosting in winter (Fig. 3).

Determination of the productive moisture reserve at the end of June showed that the reserve in the metre layer was highest under the No-till system of surface tillage. Determination of the productive moisture reserve at the end of June showed that the reserve in the metre layer was highest under the No-till system of surface tillage.

A high stock of productive moisture in the metre soil layer was under peas and soybean, but the stocks under these crops increased from ploughing to No-till after surface tillage – by 19 mm after peas and soybean – by 31 mm soybean (surface tillage) and 21 mm more under No-till after surface tillage. On average for these crops, stocks of productive moisture in June were 16–19 mm higher, or 18–21% higher. Consumption of productive moisture was highest during ploughing: 62–69 mm on average, and during surface tillage and No-till after surface loosening it was 47–48 mm, which is 1.4 times less compared to ploughing and indicates the stabilizing role of soybean and peas in summer period on soil moisture supply of crop rotation under condition of no-tillage.

Further determination in July showed that during the ripening period of winter and spring cereals, peas and soybean bean formation, the highest moisture stocks in the meter thickness were under ploughing (45 mm), while under surface tillage and No-till treatment its stocks were lower by 10 mm. Moreover, the consumption of productive moisture stocks during April-July increased from ploughing to No-till treatment after surface tillage by 15 mm.

During April-June and June-July ploughing 67% and 33% of spring moisture stocks were used; under No-till treatment after ploughing – 65% and 35%; under No-till after surface treatment – 62% and 38%, and under No-till after surface treatment – 55% and 45%, according to the periods of vegetation, which indicates a more uniform use of productive moisture stocks compared to ploughing, where the moisture is 1.2 times more intensively used in the vegetative (April-June) period in the crop rotation.

The discovered patterns of moisture storage in June are of particular value due to the fact that in 2020-2022, the average daily air temperature in June was +20.8°C against the norm +19.5°C or +1.3°C. Precipitation was 20 mm less than the long-term average (75 mm). The sum of the effective temperatures is greater than +5°C and +10°C for 2021-2022 at the end of July was +1413°C and +845°C, which is higher than the annual average temperature values for the period 1986-2015 by +35°C and 40°C. Determination of the productive moisture stocks at the end of June showed that the stocks in the metre layer were also the highest under the No-till treatment after surface tillage. The excess over stock after ploughing was +20 mm and the flow rate for April-June was lower by 15 mm, or 1.2 times lower than after ploughing. High stocks of productive moisture in the metre layer of soil were under peas and soya, but stocks under the above crops increased from ploughing to No-till after surface tillage – by 19 mm under peas and soya – by 31 mm (surface tillage) and by 21 mm more than No-till after surface tillage. On average for the above-mentioned crops, stocks of productive moisture in June were 16–19 mm higher, or 18–21% higher.

The highest consumption of productive moisture was during ploughing: on average 62-69 mm, and during surface tillage and No-till after surface tillage it was 47–48 mm, which is 1.4 times less compared to ploughing, indicating the stabilizing role of soybean and peas in summer to provide soil moisture in the crop rotation on condition of abandoning ploughing.

Of particular value, the identified patterns of moisture retention in June and even more use in April-July, are due to the fact that in 2020–2022, the average daily air temperature in June was +20.8°C with the norm being +19°C or +1.3°C. Rainfall was 20 mm less than the long-term average (75 mm). In recent years (2020–2022), as of 31 July, the sum of active temperatures is above +5°C amounting to +1425°C, which exceeds the annual average by +50°C, and the sum of the effective temperatures is higher +10°C amounting to +850°C, which exceeds the norm by +55°C. Changes in the accumulation of the sum of active and effective temperatures in relation to the mean annual values indicate a warming of the growing conditions of grain and legume crops, which justifies the expediency of development of water-saving systems and methods of cultivation, which should include the No-till treatment, in the central part of the forest-steppe of Ukraine.

DISCUSSION

Tillage compaction is a common phenomenon occurring on all intensively cultivated black soils due to the degradation of the soil structure. Its main causes are: erosion, reduced organic matter content, and pressure due to the weight of agricultural machinery. The first two reasons are related to insufficient input of organic matter into the soil and further loss of stability of the soil structure of structural particles and water-resistant aggregates. According to foreign researchers [Derpsch, 2008; Duiker & Myers, 2005; Landers, 1999; Moyer, 2011], deep soil loosening before switching to the No-till system should be carried out to a depth not exceeding the compacted layer, which is related to deep soil ploughing aimed, according to the authors, at improving the physical condition of the soil and, above all, its porosity. Deep loosening is carried out as a one-time application without the need for repetition, and a set of measures available in effective farming will be used later to avoid compaction problems: production of a maximum amount of plant matter to cover the soil surface; use of cover crops for sideration; rational crop rotation; biological activity in the soil, including worms and insects that loosen the soil. The soil is loosened or deeply loosened when switching to No-till with heavy farm machinery [Derpsch, 2008; Duiker & Myers, 2005; Landers, 1999; Moyer, 2011]. An abrupt transition approach to minimum tillage and No-till systems is used, which in most cases discredits the idea of minimum tillage on black soils in agrocenoses due to their extreme degree of agrophysical degradation.

In the conceptual provisions of the new technical policy [Baker et al., 2007] in farming of Ukraine, minimal tillage of black soils is the main direction of improvement of interaction between soil and machine-tractor aggregates in relation to the root layer, reducing the role of minimal tillage to eliminate xenobiotic influence on the formation of soil structure in the humus horizon of black soils towards natural processes of structure formation.

Long-term research of scientific school of soil-protective and biological farming of N.K. Shikula established that systematic performance of soil-protective minimum tillage of black soil enhances facial and functional-ecological regularities of soil formation of black soil in agrocenoses by improving hydrothermal conditions in the annual and seasonal cycles, as well as by activating the biological factor of soil formation during the drought-resistant period of crop vegetation, which enhances the soil-restorative activity of the living root systems of agricultural crops in the process of restoration of the agrophysical state of black soils in agrocenoses [Medvedev, 2013].

Minimum tillage of black solis with surface embedding of organic and mineral fertilizers, stubble and root residues with creation of an organic mulch layer on the soil surface is a factor of reproducing thermodynamically appropriate structure of pore space structure of humus-enriched black soil thickness (0–70 cm) by increasing the volume of aggregate pores, in which the productive moisture is constantly in a state of phase transition in an optimum ratio with compressed soil air, forming a generalising constantly pulsating water meniscus under the influence of external climatic factors. The indicated state of moisture in the porous medium determines the level of energy saturation of black soils, the direction of external energy flows and the intensity of subordinate local processes of agrophysical, biochemical nature in the elementary volume of the black soil body [Demidenko & Shikula, 2007; Demidenko & Velichko, 2013].

The restoration of the agro-physical properties of black soil is determined by the thickness of the mulch layer of crop residues, by-products of crop rotations that remain after harvesting and the straw part of manure after it has been applied and incorporated into the upper part of the humus horizon of black soil. The formed organogenic layer (0–15 cm) of black soil must necessarily be covered by a layer of legume crop residues and by-products of tilled crops, and there must be no demarcation between the layer of plant mulch and the soil surface, i.e. the mulch layer must not lie on a non-bio-active (biologically inactive) field surface. The plant organic matter from the lower part of the mulch layer should be gradually involved in the small-scale biological cycle (SBC) of matter and energy. Over the years of systematic implementation of conservation tillage, the organogenic 0–15 cm layer of black soil and the layer of annually renewable mulch after harvesting crops should consist of an organic whole, which should not be destroyed by deep intensive tillage, but should be built up by conservation tillage, which is a necessary condition for a risk-free conversion to the No-till treatment.

Minimum tillage of black soil in the rotation in the 8-9 th year contributes to the disappearance of «plough foot» from systematic ploughing at a depth of 30–32 cm, which reduces the value of contact resistance of moisture flow at this depth when filtering atmospheric precipitation and mobilization of deep stores of soil moisture. Shifting the plane of increased contact resistance of moisture to the soil surface (5–8 cm), above which there is a layer of black soil enriched with root and crop residues of different decomposition stages (detritus) and the presence of a layer of annually renewable plant mulch on the soil surface, creates a model of the most perfect, in agrophysical terms, structure of humus horizon (0–40 cm) of the soil column of cultivated black soil.

The regrouping of water-resistant aggregates and structural detritus from the smallest fractions into the most valuable sizes (5–1 mm and 3–0.5 mm) forms the textural porosity, which reflects the ultimate level of soil compaction during drying and determines the volume of pores containing soil biota resources. As a result of the restoration of agrophysical self-regulation in the soil, the homogeneity of the porous space is increased, creating a certain amount of surplus size, which is typical for structural particles of 1–5 mm in dry dispersion and water-resistant aggregates of >1 mm in wet dispersion [Demidenko, 2008; Demidenko & Velichko, 2013].

Increasing the water resistance of the soil structure stabilises the ratio of pore volume occupied by moisture to pore volume occupied by air at a ratio of 1.5–1.7 to 1 relative to total moisture content and 1.3–1.4 to 1 relative to productive moisture content. With the same values of structural density during ploughing and minimum tillage, there is a qualitative change in the porous medium in favour of the volume of pores occupied by moisture in relation to the volume of pores occupied by air.

To switch to systematic minimum tillage (hereafter referred to as No-till treatment) of black soil, which is in a critical state of agrophysical degradation, 5 to 7 years of systematic application of conservation tillage with surface incorporation of fresh organic matter is required, which provides a medium level of agrophysical restoration or simple reproduction of soil fertility of black soil in agrocenosis [Demidenko & Shikula, 2001]. In the eighth year of systematic conservation tillage, a systematic minimum tillage in the rotation and subsequently a No-till system in the agrocenosis can be safely transitioned (Table 6).

The nature of the unstable soil condition during the first years of systematic application of minimum tillage and the No-till treatment of black soils, which are in an extreme stage of agrophysical degradation, is that the low content of the most valuable fractions of structural particles and water-resistant units in the total agronomically valuable units is at a critical level, which reduces the productive use of moisture from the soil by 30–40% [Demidenko & Shikula, 2001].

Lack of differentiation of tilled soil layer by structure density, which is typical for ploughed black soils, intensive degumification and agrophysical degradation contribute to formation of cloddy-dense structure of humus horizon, while in natural cenoses and in conditions of soil-protective tillage a fine cloddy-rubble structure of humus horizon is formed. After the abandonment of systematic ploughing, it takes 3–4 years to form an optimum 0–30 cm layer of black earth, according to the principle: loose (0–10 cm) – compacted (10–20 cm) – loose (20–30 cm). Until this structure is formed, the soil, as a system, is very unstable in relation to changes in weather and climatic factors when they deteriorate. By midsummer, the density of the structure in the 0–30 cm soil layer can reach values of 1.35–1.40 g$\cdot$cm^{-3} and higher, and total porosity can be reduced to 42–45%, which increases the physical evaporation of soil moisture [Demidenko, 2004; Demidenko & Shikula, 2006; Demidenko, 2001; Krylach, 2022]. Unrecovered ability of interconnected pulsation of

Table 6. Effect of conservation tillage on the level of self-organisation of medium and heavy loam-podzolic black soils in the forest-steppe zone crop rotations since the transition to its systematic application

Level of agrophysical self-organisation, number of years since application of conservation tillage	Unit size, mm; content, %		Level of minimum tillage in the crop rotation	Level of minimum tillage in crop rotation
	Structural particles >0.25 2–5	water-resistant units >0.25 0.5–3		
Low: 4 years	60–65 25–30	<45 25–35	Shallow no-tillage at varying depths of 22–25 cm	Descending level of fertility
Medium: 5–8 yeras	65–75 35–45	55–65 45–55	2 times per rotation no-tillage at 22–25 cm under other crops 5–12 cm	Simple reproduction
High: 9–10 years	75–80 45–55	70–75 55–65	Systematic minimum and zero treatment	Extended reproduction fertility

annual and seasonal cycles of humus and agrophysical properties, surface application of mineral fertilizers, stimulating root system development by turf type, in critical weather-climatic conditions break the homeostatic equilibrium in the soil-plant-atmosphere system. The potential of the layer of plant mulch that remains on the field surface is limited and the self-regulating capacity of black soil is low. For this reason, multi-depth conservation tillage is a 'buffer' period during the transition to complete minimum tillage, allowing a rapid transition to simple fertility reproduction on black soils. It should be applied depending on the granulometric composition and humus content of the humus horizon for the first 3–5 years after ploughing is abandoned [Shikula & Demidenko, 2004; Shikula & Demidenko, 2005].

Production conditions of agrocenoses allow to restore natural structure formation, reproduce the process of physical regradation of black soils and, due to application of soil-protection tillage, accelerate restoration of soil structure for the first 3–5 years after abandoning ploughing, quickly bringing the level of soil fertility from the downward state to the level of simple reproduction. From 6–7 years onwards, starts a risk-free transition to systematic use of 5–12 cm tillage and No-till treatment, accelerating the process of restoring the state of expanded fertility reproduction through the reproduction of natural soil formation in agrocenoses [Demidenko & Shikula, 2006]. Thus, we found that:

- on degraded black soils during transition to minimum soil-protecting tillage (planning of transition to No-till treatment in agrocenosis) for the first 3–5 years, depending on the degree of agrophysical degradation, granulometric composition, humus content, we should apply soil-protecting (or chisel) tillage at 22–25 cm with the use of crop residues (straw, corn, sunflower stalks, buckwheat and other crops) as an organic fertilizer, ensuring the energy of soil formation in the forest-steppe;
- the main task entrusted to this period is to achieve the regrouping of structural particles and water-resistant aggregates from the smallest fractions into the most valuable ones and the formation of textural porosity, which would reflect the ultimate level of soil compaction during drying and define a sustainable pore volume containing soil biota resources, thus creating a predominant number of pores characteristic of structural particles of 2–5 mm and water-resistant aggregates of 0.5–3 mm, stabilising at an optimum level the ratio of pore volume occupied by moisture to pore volume occupied by air. This will be the parameterisation of the physical state of black earth to an equilibrium state, which is a necessary condition for minimising black earth cultivation in agrocenoses;
- at the time of the transition to systematic minimum tillage and the No-till treatment, black soils disappear under the influence of conservation tillage in the humus horizon at a depth of 30–32 cm, the "plough foot" from ploughing, and the plane of increased moisture contact resistance moves to the soil surface (5–8 cm), above which there is a black soil layer enriched with root, crop residues of different decomposition stages or detritus, with a layer of annually renewable vegetative mulch formed on the soil surface, which creates a model of the most perfect, in the agrophysical sense, construction of the upper part (0–40 cm) of the soil thickness of cultivated black soils and allows a risk-free transition to systematic minimum tillage on 5–12 cm with the subsequent application of the No-till treatment;
- the duration of transition (conversion) period, when periodic deep soil-protecting cultivation is applied, at the border of Forest-Steppe and Steppe zones (humus content > 4.0%, granulometric composition – heavy loam and light clay, precipitation, 450 mm), is 4–5 years. In northwest direction from the strip of demarcation of soil-climatic zones transition period increases up to 7–8 years (humus < 4%, light granulometric composition, precipitation > 500 mm).

CONCLUSIONS

Among all parameters, the ratio of pore volume with moisture to aeration pore volume is the most indicative. The ratio optimisation (1 to 1) increases by a factor of 1.81 under No-till treatment after ploughing, by a factor of 1.98 after surface tillage and by a factor of 2.68 under No-till treatment after surface tillage. At density 1.21–1.25 g·cm^{-3} the ratio varies in a series of increases of 0.65 to 1, 0.85 to 1, 0.90 to 1 and 0.95 to 1, respectively. The implementation of No-till treatment on a 7-year old surface tillage agronomic background allowed the formation of productive moisture stocks in crop rotation at 154 mm, which was at the level of the stocks on the plough and significantly higher than under systematic surface tillage. The ratio of moisture stocks in the 0–50 cm and 50–100 cm layers was 0.9 to 1 in the crop rotation. Under the crop rotation, the ratio was 0.90–0.94 to 1, indicating more intensive moisture diffusion in the one-metre thickness and concentration in the 50–100 cm thickness.

It was found that during the April-June and June-July periods, 67% and 33% of the spring moisture stocks were consumed with ploughing; with No-till after ploughing, 65% and 35%; with surface tillage – 62% and 38%, and with No-till treatment after surface tillage – 55% and 45%, which indicates a more optimal use of productive moisture stocks compared to ploughing, where moisture is used 1.2 times more intensively in the spring-summer vegetation period of April grain and leguminous crops in the crop rotation.

With No-till treatment on the 7-year agronomic background of surface tillage, the deviation from the average value of productive moisture stocks under the crops of the rotation was the lowest compared to systematic ploughing and No-till treatment after ploughing, which is associated with the optimization of agrophysical properties of 0–30 cm layer of black soil and the presence on the soil surface of a layer of plant mulch from predecessors, which guaranteed less soil freezing and accumulation of more snow in the winter period.

When converting to No-till treatment in a 5-field grain crop rotation, a transition period with soil-protecting one-time deep loosening or surface loosening followed by permanent surface loosening at 10–12 cm should be applied, which in 5 years will contribute to overcoming the manifestations of agrophysical degradation of podzolic black soil through the reproduction of humus, structural condition and water resistance of the structure. It will also ensure the achievement of an equilibrium state of structural density, the most optimal ratio of pore volume occupied by moisture to air at an optimum level, thus guaranteeing restoration of the soil mechanism for regulating physical evaporation of productive moisture stocks, compared to systematic ploughing and No-till treatment after ploughing in a sharp transition where the manifestation of agrophysical degradation remains at a high level.

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