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Dynamics of The Humus Content Under Different Chernozem Treatment Conditions

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ABSTRACT

The humus content in the soil is the most important factor affecting the yield of agricultural crops. The research of the impact of the soil cultivation methods upon the humus content is an urgent scientific and practical task of modern agriculture. This paper analyzed long-term (45 years) field experiments on the impact of ploughing, deep and shallow non-moldboard tillage upon the humus content in the chernozem soil of central Ukraine. The research materials reflect a broad picture of influence of the processing methods upon the accumulation of total humus. For example, with respect to ploughing with deep non-mouldboard cultivation, accumulation of the total humus in the 40th year of research, was +0.0028%; with shallow non-mouldboard cultivation it was +0.0005%.

Keywords: black soil, humus, content, non-mouldboard tillage, ploughing.

INTRODUCTION

Preservation of soil fertility has attracted great interest in the scientific literature (Hakansson 2005; Kaminski, 2011; Barwicki et al. 2012; Skrypchuk et al. 2020). At a long-term anthropogenic load upon the soil agro-ecosystem, both the humus content and its qualitative composition change (Cvei et al. 2016; Novakovska et al. 2016). Not only the morphological and basic physicochemical properties of the soil, but also the water, air, and thermal conditions are closely related to the humus reserves and its qualitative composition (Wojciechowski et al. 2020; Šimanský et al.2019; Eremin, 2016). Simultaneously with the decrease in the humus content, there is a decrease in the proportion of soluble humus fractions, which are more resistant to mineralisation (Biradar et al., 2020; Eremin, 2009).

In the world agriculture, the fundamental foundations of the new agrarian policy were formulated in the second half of the last century. This is environmental protection and active support of the soil protection technologies. After all, following prolonged deep cultivation and intensive chemicalisation, a decrease in biodiversity and deterioration in agronomically important soil properties were noted. The non-mouldboard tillage technologies have found wide application in many countries. The growing demand for the products of the agro-food sector requires a search for innovative (soil-protective) ways of achieving the sustainable development goals under the conditions of a changing climate and the loss of biodiversity (FAO, 2021).

In connection with the development and acquisition of a soil-protective system of agriculture, long-term studies are carried out of the impact of long-term mouldboard, non-mouldboard and minimal tillage upon the accumulation of humus in the chernozem. However, the published materials are of a contradictory nature to the changes in the humus content in the cultivated chernozem layer under the impact of different tillage systems (Demidenko et al. 2018; Tonkha and Yevpak, 2016). Practically all the researchers remark that the systematic use of non-mouldboard deep and shallow tillage leads to a sharp differentiation of the arable layer in terms of fertility (Balaev et al., 2020; Pikovska and Vitvicka, 2016; Prihodko et al., 2013; Khokhlova et al., 2014).

The ambiguity of the results of these studies indicates that, under different soil and climatic conditions, the impact of factors that determine transformation of humus, using different methods of tillage, is not the same (Khokhlova et al., 2015; Kuznetsova et al., 2010.

One of the most acute problems of modern agriculture in Europe is degradation of the zonal soils, including the Ukrainian chernozems (Boyko et al., 2018). The importance of the organic matter of chernozem can hardly be overestimated, both in terms of the agronomic soil science and imparting stability to the terrestrial ecosystems as well as, above all, agroecosystems. The special role of soil organic matter is connected with its global impact upon all the agronomic properties of soil (physical, chemical, biological), as well as its energy value (Centilo et al., 2019).

The effect of the organic matter in chernozem largely depends on the conditions of transformation of the plant residues coming into the cultivated layer of the soil. Due to the application of intensive farming methods, the problem of maintaining humus in the soil under modern conditions becomes even more relevant, and many studies have been devoted to its study. Despite some differences in the results, which may be largely due to the zonal soil and climatic features, it is undeniable that tillage is the most energy-intensive, problematic and debatable element of the farming system (Tovstykh, 2018), and the study and analysis of the results of experiments in this area is the task of science.

The purpose of this work was to summarise and analyse the research materials in a long-term stationary field experiment (45 years) regarding the dynamics of accumulation and mineralisation of the total humus in a typical low-humus chernozem, depending on various methods of cultivation (ploughing to the depth of 22–25 cm, non-moulboard tillage to the depth 22–25 cm and shallow non-mouldboard tillage to the depth of 10–12 cm).

MATERIALS AND METHODS

The investigations were conducted in the Central part of Ukraine in a long-term stationary experiment at the Cherkasy Experimental Station of the National Scientific Center "Institute of Agriculture" (49º57′N, 32º19′E). The field stationary experiment was founded in 1975 and has been carried out up to now (Zaryshnyak et al., 2016). The soil background of the experiments: typical low-humus coarse-silty light loamy chernozem with the humus content 3.8–4.2%, mobile phosphorus 12–14 mg·(100 g)$^{-1}$ soil, mobile potassium 8–10 mg·(100 g)$^{-1}$ soil, saline pH 6.8–7.0. The investigatons were carried out against the background of a 5-field crop rotation: 60% – cereals; 20% – sugar beet; 20% – perennial grasses, with the following alternation of crops: winter wheat – sugar beet – barley + grasses – perennial grasses. In the period between 1975 and 1990, an average of 7.5 t ha^{-1} of cattle manure (+ $N_{112}P_{100}K_{120}$) was applied. During 1990–2020, the fertilizer system was in the following variants: $N_{66}P_{66}K_{82}$ per 1 ha of the crop rotation area 6.5 t·ha^{-1} by-products of the crop rotation crops –winter wheat and barley straw, sugar beet tops and stubble residues of perennial grasses (for brevity, the term "by-products" was used in the text below).

Under the conditions of a field stationary experiment the impact of various tillage methods of chernozem upon the content of the total humus was studied. The methods of tillage in a five-field crop rotation were as follows: ploughing at 22–25 cm; non-mouldboard tillage – at 22–25 cm and shallow non-mouldboard loosening – at 10–12 cm with flat cutters-rippers. Each tillage method included its own set of technological operations – from harvesting the predecessor to performing the main cultivation. The principle of systemic difference was applied.

The methodological organisation of the experimental plots did not change throughout the years of research. The size of the sown area of the plot was 166 m^2, the accounting area was 100 m^2, the repetition was 3-fold.

The content of the total humus was determined according to the methods which, correspondingly, are most fully reflected in the standards (Standard DSTU 4732:2007; Venglinskyi et al., 2015). The assessment of the humus content was made in the soil layers 0–20 cm and 20–30 cm. For the analysis, the data of the total humus were used in various years, taken from scientific reports and authors' own data in the period after 2000 to 2020. The results of field studies were processed using the dispersion, cluster, factor and other methods of mathematical statistics (Welham et al., 2015). The fractal estimation of the series of dynamics of humus, and the yield of the grain crops was made in accordance with the works (Moiseev et al., 2014; Kiselev, 2007). Generalisation of the research results was carried out by means of the "STATISTICA-10" software package, using non-parametric statistics and correlation analysis.

RESULTS AND DISCUSSION

Table 1 shows the dynamics of the total humus during systematic ploughing, deep and shallow tillage of typical chernozem. The starting content of humus in 1975 in various options of the soil tillage differed a little from each other, which is due to the diversity of the humus content in the humus horizon. The variability was up to 2–5%. The calculation of $LCD_{0.05}$ showed that in fact this indicator reached 0.05–0.06%, and the spread of the humus content was within the range of an unreliable difference. Therefore, the presented values were taken as the starting ones.

The comparative dynamics of the total humus indicates that during systematic ploughing, the change in the content of the total humus in the soil layers of 0–20 cm, 20–30 cm and 0–30 cm takes place according to a downward trend. In deep non-mouldboard tillage, the trends in the dynamics of the total humus were increasing; in shallow tillage in a 0–20 cm soil layer they were increasing; whereas in the soil layers of 20–30 cm and 0–30 cm they went downward.

Assessment of the series of dynamics of the total humus (Table 2) shows that the fractal dimension and the Hurst exponent fall within the range of $0.5 < H \leq 1$ or $1 < D < 1.5$, which characterises the trend (persistence) at the level of "the black noise" and the time sequence of the humus dynamics as trend-resistance; that is, the change in the content of the total humus, demonstrated by the time series in certain tillage, indicates continuation of the trend of growth or decrease, both in

Table 1. Dynamics of the total humus depending on different methods of cultivation of a typical low-humus light loamy chernozem in 1975–2020

Depth of the soil layer, cm	Years of observation						
	1975	1985	1990	1995	2010	2015	2020
Ploughing							
0–20	3.91	3.92	3.89	3.98	3.85	3.75	3.70
20–30	3.70	3.71	3.70	3.73	3.75	3.60	3.55
0–30	3.81	3.82	3.80	3.86	3.80	3.68	3.60
± in relation to ploughing							
Non–mouldboard tillage to the depth of 22–25 cm							
0–20	-0.06	+0.04	+0.16	+0.05	+0.14	+0.10	+0.25
20–30	-0.04	-0.11	+0.07	-0.02	-0.01	+0.11	+0.13
0–30	-0.05	-0.17	+0.11	+0.01	+0.07	+0.18	+0.23
Non–mouldboard tillage to the depth of 10–12 cm							
0–20	-0.03	-0.19	+0.12	0.00	+0.04	+0.10	+0.06
20–30	-0.02	-0.14	+0.07	-0.28	-0.26	-0.05	-0.13
0–30	-0.03	-0.17	+0.09	-0.14	-0.11	+0.02	-0.01
$LCD_{0.05}$							
0–20	0.06	0.09	0.07	0.05	0.07	0.09	0.09
20–30	0.05	0.09	0.08	0.05	0.06	0.09	0.09
0–30	0.06	0.09	0.08	0.06	0.06	0.08	0.07

the past and in the future. In addition, the higher the value of indicators H and D, the more often its rise is followed by a rise, and a decline is followed by a decline.

Typification of the parameters of the total humus dynamics for various methods of tillage (Table 3) showed that, according to the general model, the coefficient of variation of the total humus was within the range of 2.47–2.92%. The average value of the total humus coincides with the median values. The amplitude range is Δ_{0-20} = 0.35 %, Δ_{20-30} = 0.7%, Δ_{0-30} = 0.32%, and the normalised range for the 50% probability level is Δ_{0-20} = 0.18%, Δ_{0-20} = 0.14%, Δ_{0-20} = 0.15%.

During ploughing, the coefficient of variation in the content of the total humus varied within 2.0–2.57% and was lesser than the general model. The amplitude range of the humus content did not go beyond the interval of the general model, since the normalised range was at the 50% significance level. When performing deep non-moldboard tillage, the coefficient of variation in the humus

Table 2. Fractal assessment of the series of dynamics of the total humus depending on various methods of tillage of typical chernozem in 1975–2020

Depth, cm	Equation of the trend , $Y=a*e^{\pm bx}$	Reliability of the trend, R^2	*Fractal dimension, *D*	**The Hurst exponent, *H*	Dynamic series status
Ploughing to the depth of 22–25 cm					
0–20	$y = 4.00e^{-0.01x}$	0.62	1.01	0.99	Persistent
0–30	$y = 3.90e^{-0.009x}$	0.58	1.01	0.99	
Non–mouldboard tillage to the depth of 22–25 cm					
0–20	$y = 3.87e^{0.006x}$	0.35	0.99	1.01	Persistent
0–30	$y = 3.76e^{0.0045x}$	0.39	0.99	1.01	
Non–mouldboard tillage to the depth of 10–12 cm					
0–20	$y = 3.86e^{0.0005x}$	0.34	0.99	1.01	Persistent
0–30	$y = 3.79e^{-0.005x}$	0.39	1.01	0.99	

Note: * D = 1 – |±bx|, ** H = 2 – D.

Table 3. Typified parameters of the humus state of a typical chernozem depending on various tillage systems in 1975–2020

Depth, cm	Content of the total humus, %								the coefficient of variation,%;
	Average, *X*	Median, $L_{0.50}$	Amplitude rage		Normalised range with a probability:				
			Δa = max – min		50%		10%		
			min	max	$\Delta(50) = L_{0.75} - L_{0.25}$		$\Delta(10) = L_{0.90} - L_{0.1}$		
					$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.90}$	
Ploughing to the depth of 22–25 cm									
0–20	3.86	3.89	3.70	3.98	3.75	3.92	3.70	3.98	2.57
20–30	3.68	3.71	3.55	3.75	3.60	3.73	3.55	3.75	2.01
0–30	3.77	3.80	3.60	3.86	3.68	3.82	3.60	3.86	2.45
Non–mouldboard tillage to the depth of 22–25 cm									
0–20	3.96	3.99	3.75	4.05	3.95	4.02	3.75	4.05	2.51
20–30	3.70	3.71	3.61	3.77	3.66	3.74	3.61	3.77	1.43
0–30	3.83	3.86	3.71	3.91	3.78	3.87	3.71	3.91	1.76
Non–mouldboard tillage to the depth of 10–12 cm									
0–20	3.86	3.85	3.73	4.01	3.76	3.98	3.73	4.01	2.77
20–30	3.65	3.55	3.42	3.73	3.45	3.68	3.42	3.73	3.38
0–30	3.71	3.72	3.59	3.87	3.65	3.74	3.59	3.87	2.33
$LCD_{0.05}$									
0–20	0.09		-	-	-	-	-	-	-
20–30	0.05		-	-	-	-	-	-	-

Note: $L_{0.1} - L_{0.90}$ the quantile value.

content was 1.05–2.04 times lesser, relative to the general model. In the soil layers of 20–30 cm and 0–30 cm, the coefficient of variation was 1.4 times lesser, also relative to systematic ploughing. The amplitude range went beyond the values of the general model in the soil layers of 0–20 cm and 0–30 cm, both during ploughing and the general model. In the soil layer of 20–30 cm, the amplitude range was within the values of the general model and the values during ploughing. The normalised range at the 50% significance level had a similar pattern, which was established for the amplitude range.

In shallow non-mouldboard tillage, the coefficients of variation in the content of the total humus exceeded the value during ploughing and deep non-mouldboard tillage in the soil layers of 0–20 cm and 20–30 cm by 1.08–1.10 times and 1.68–2.36 times, respectively. The values of the amplitude and normalised range in the soil layer of 0–20 cm went beyond the values of the general model, but were within the limits of the values during ploughing and deep ploughless tillage. According to the average value, the content of the humus was significantly higher with deep non-mouldboard tillage. The excess relative to ploughing was 0.10% in the soil layer of 0–20 cm; 0.02% of 20–30 cm and 0.06% in the soil layer 0–30 cm.

With shallow non-moldboard tillage, the average humus content was significantly lower in comparison with ploughing and deep non-mouldboard tillage, as well as relative to the general model. Attention was drawn to a decrease in the total humus in the soil layer of 20–30 cm, which was less by 0.03–0.15% in relation to ploughing, deep non-mouldboard tillage and the general model, which is associated with an increase in the coefficient of variation by 1.16–2.36 times, relative to the deep tillage and general model. Dynamics of the total humus in various treatment systems is divided into two periods: a period of manure application (15 years) and a period (25 years) of the use of by-products as organic fertilisers (Table 4).

It has been established that application of 7.5 $t \cdot ha^{-1}$ manure against the background of a mineral fertiliser ensured an increase of humus in relation to arable land in 1990 +0.07–0.16% and +0.07–0.12% in the soil layers of 0–20 cm and 20–30 cm, in accordance with deep and shallow ploughless tillage. With introduction of by-products of crop rotation as an organic fertiliser, the process of humus accumulation during non-moldboard tillage decreased sharply (1995), and in the 10th year, there was a tendency to accumulate the total humus during deep ploughless tillage, and there was a steady trend of its decrease in shallow ploughless tillage.

Table 4. Dynamics of the total humus of typical chernozem depending on the long-term use of various tillage systems in 1975–2020

Depth, cm	Years o observation:					
	1985	1990	1995	2010	2015	2020
	Manure, 7.5 $t \cdot ha^{-1}$			By-products, 6.5 $t \cdot ha^{-1}$		
Ploughing to the depth of 22–25 cm						
0–20	3.92	3.89	3.98	3.85	3.75	3.70
20–30	3.71	3.70	3.73	3.75	3.60	3.55
0–30	3.81	3.80	3.86	3.80	3.68	3.60
± before ploughing						
Non–mouldboard tillage to the depth of 22–25 cm						
0–20	+0.04	+0.16	+0.04	+0.14	+0.10	+0.25
20–30	-0.11	+0.07	-0.02	-0.01	+0.11	+0.13
0–30	-0.17	+0.11	+0.01	+0.07	+0.11	+0.23
Non–mouldboard tillage to the depth of 10–12 cm						
0–20	-0.19	+0.12	0.00	+0.04	+0.10	+0.06
20–30	-0.14	+0.07	-0.28	+0.26	-0.05	-0.13
0–30	-0.17	+0.09	-0.14	-0.11	+0.02	-0,01
LCD_{05}						
0–20	0.09	0.10	0.07	0.06	0.09	0.09
20–30	0.10	0.08	0.09	0.07	0.09	0.10
0–30	0.09	0.10	0.06	0.08	0.08	0.07

Only in the 20th year of the systematic use of by-products as fertilisers, a significant increase in the humus content in the 0–30 cm deep layer was obtained with deep tillage (+0.10–0.18%) and an increase in the humus content in the 0–20 cm layer with shallow non-moldboard tillage, while simultaneously reducing the humus content in the soil layer of 20–30 cm.

Calculation of the dehumification rate relative to the basic indicator of the humus content in 1975 made it possible to establish an impact of various processing methods and the type of organic fertilisers upon the dehumification intensity in time (Table 5). During the period of manure application in the first 10 years of research (1975–1985) with systematic ploughing, an increase was established in the humus content in the 0–30 cm soil layer by +0.01% or +0.001% annually. Using deep non-mouldboard tillage in the soil layer of 0–20 cm, the increase in the humus content was +0.21% or +0.021% annually, while the humus content in the soil layer of 20–30 cm decreased annually by -0.06% or -0.006%. With systematic shallow tillage during this period, a decrease in the content of the total humus by -0.07–0.11% or -0.007–0.011% annually was recorded. A particularly intense process of dehumification occurs in the soil layer of 20–30 cm. After 15 years of implementation of various systems for the treatment typical chernozem when manure was applied under the conditions of ploughing, a decrease in the humus content relative to the base value by -0.01–0.02% or -0.0007–0.013% annually was revealed, while with deep non-mouldboard processing, the content of the total humus increased by +0.11 -0.3% or +0.007–0.02% annually. A similar regularity was established for shallow non-mouldboard tillage: the increase in the humus content was +0.05–0.21% or +0.03–0.014% annually. What is particular, is that with non-mouldboard tillage the humus content in a 0–20 cm layer of typical chernozem intensively increases. When manure is replaced with by-products as an organic fertiliser (1990–2015), regardless of the method of tratment, dehumidification or a decrease in the rate of humus accumulation in the 0–30 cm layer of chernozem occurs. The highest rates of dehumification were found during systematic ploughing: the humus content decreased by -0.18–0.30% or -0.007–0.012% annually.

In deep non-mouldboard treatment, the dehumification process also intensified: by 0.05–0.06% or -0.002% annually. When performing shallow non-mouldboard tillage, dehumification was 3 times greater compared to the deep non-moldboard tillage, and 1.58 times higher compared to ploughing. An assessment of the dehumification of chernozem during 40 years of applying various tillage systems showed that with systematic ploughing, dehumification was -0.19–0.32% or -0.005–0.008% annually. In the case of deep non-mouldboard tillage, an increase was obtained in the content of the total humus in a layer of 0–30 cm by +0.015% or +0.004% annually. The highest increase in the humus content was in the 0–20 cm chernozem layer (+0.25% or +0.006%

Table 5. Rates of mineralisation and accumulation of humus depending on the long-term use of various systems for processing typical chernozem in 1975–2020

Depth, cm	Application of organic fertilisers in the form of:					
	Manure, 7.5 t·ha^{-1}			By-products, 6.5 t·ha^{-1}		1975–2020 (45 years)
	1975 (basic)	1975–1985 (10 years)	1975–1990 (15 years)	1990–2015 (25 years)	1975–2015 (40 years)	
Ploughing to the depth of 22–25 cm						
0–20	3.91	+0.01	-0.01	-0.18	-0.19	-0.21
20–30	3.70	+0.01	-0.02	-0.30	-0.32	-0.15
0–30	3.81	+0.01	-0.01	-0.27	-0.28	-0.18
Non–mouldboard tillage to the depth of 22–25 cm						
0–20	3.85	+0.21	+0.30	-0.05	+0.25	+0.20
20–30	3.66	-0.06	+0.11	-0.06	+0.05	+0.02
0–30	3.71	+0.07	+0.20	-0.05	+0.015	+0.11
Non–mouldboard tillage to the depth of 10–12 cm						
0–20	3.88	-0.07	+0.21	-0.16	+0.05	-0.04
20–30	3.68	-0.11	+0.05	-0.18	-0.13	-0.26
0–30	3.74	-0.09	+0.13	-0.17	-0.04	-0.15

annually). In the case of shallow non-mouldboard tillage in a soil layer of 0–30 cm, a decrease in the content of the total humus by -0.04% or -0.001% annually. In the soil layer of 0–20 cm an increase in the content of humus by +0.05% or -0.0013% annually was recorded, and in the soil layer of 20–30 cm, the content of the total humus decreased by -0.13% or -0.0033% annually. The obtained data about the growth of the total humus content or dehumification allow establishing the rate of dehumification of typical chernozem -0.005–0.008% annually with systematic ploughing and the possible growth rate of the humus content by +0.001–0.006% annually. The rate of enrichment with humus in a 0–20 cm layer of a typical layer in non-moldboard tillage is +0.0013–0.006% annually, and the rate of decrease in the humus content in a layer of 20–30 cm in shallow non-mouldboard tillage is -0.0033% annually. The phenomenon of enrichment with the total humus of 0–20 cm of a typical chernozem layer during the non-mouldboard tillage is connected with differentiation of the cultivated chernozem layer. A calculation showed that during ploughing a close correlation was found (R = +0.87; R^2 = 0.77), and in the 0–30 cm layer R = +0.97 ; R^2 = 0.94 between the humus content in the 0–20 cm soil layer and the content in the 20–30 cm layer. In non-mouldboard deep tillage, the relationship of the humus content between the soil layers of 0–20 cm and 20–30 cm weakened to an average level of correlation (R = +0.55; R^2 = 0.29), but with the soil layer of 0–30 cm, the relationship was at the level of a direct strong correlation (R = +0.93; R^2 = 0.87). When performing shallow non-mouldboard tillage, the correlation of the humus content between the soil layers of the cultivated 0–30 cm layer weakened to a low level of correlation (R = +0.21; R^2 = 0.04), and in the soil layer of 0–30 cm, the correlation decreased in comparison with ploughing to the level R = +0.79; R^2 = 0.62. It was revealed that in systematic ploughing, per unit of increase in the humus content in the 0–20 cm soil layer, there is an increase of 0.6 units of the humus content in the soil layer of 20–30 cm,but in non-mouldboard tillage the growth decreases to 0.21–0.26 humus units. If the per unit growth of the humus content in the 0–20 cm soil layer during plowing accounted for 0.9 growth units of the humus content in the 0–30 cm soil layer, then with non-mouldboard tillage, the indicated increase was 0.63–0.64 units of the humus content. During the period of research, the yield of the grain crops, regardless of the method of tillage, increased: during plowing by 1.66 t·ha^{-1}; during deep non-mouldboard loosening – by 1.61 t·ha^{-1}, and during shallow non-mouldboard tillage – by 1.44 t/ha, which is 1.12–1.15 times less compared to ploughing and deep ploughless loosening. The yield of the grain crops in the period 2016–2020 was at the level: 6.51 t·ha^{-1}, 6.48 t/ha, 6.06 t/ha (LCD$_{0.95}$=3.5 t·ha^{-1}), respectively. In deep non-mouldboard loosening, the yield trend of the grain crops was within an insignificant difference compared to ploughing, while in shallow subsurface loosening, there was a significant difference in the yield change trend over the entire research period (Fig. 1).

A high level of productivity of the grain crops in a crop rotation with perennial grasses during deep non-mouldboard tillage is ensured by the stabilisation of the yield of winter wheat and corn, which was at the level of ploughing for all the specified parameters of the normalised range. The coefficient of variation for winter wheat was ~11.1%, and for corn ~28%. In turn, as with shallow non-mouldboard tillage, the yield of winter wheat was significantly lower, as was the yield of corn in comparison with ploughing. The value of the coefficient of variation of the corn yield exceeded 30%, which indicates instability of the yield in time (Fig. 1). By systematic implementation of deep non-mouldboard loosening of typical chernozem in a 5-field grain-row crop rotation, the formation of the grain crop yields occurs against the background of an increasing content of total humus. In addition, the grain yield has a slight tendency to increase in comparison with the systematic ploughing, in which the dynamics of the total humus exhibited a negative trend. The yield of the grain crops with systematic shallow non-moldboard loosening was significantly lower during the entire period of the study, compared to ploughing and non-mouldboard loosening.

Authors' previous studies have shown (Demydenko et al., 2013) that the method of soil cultivation determines the placement of the bulk of organic residues and manure in the cultivated chernozem layer, which leads to its differentiation by biogenicity. Embedded in the upper layer, the plant residues, organic and mineral fertilisers during non-mouldboard treatment create favorable conditions for the vital activity of aerobic microorganisms, which positively affects the quantitative and qualitative state of humus and is associated

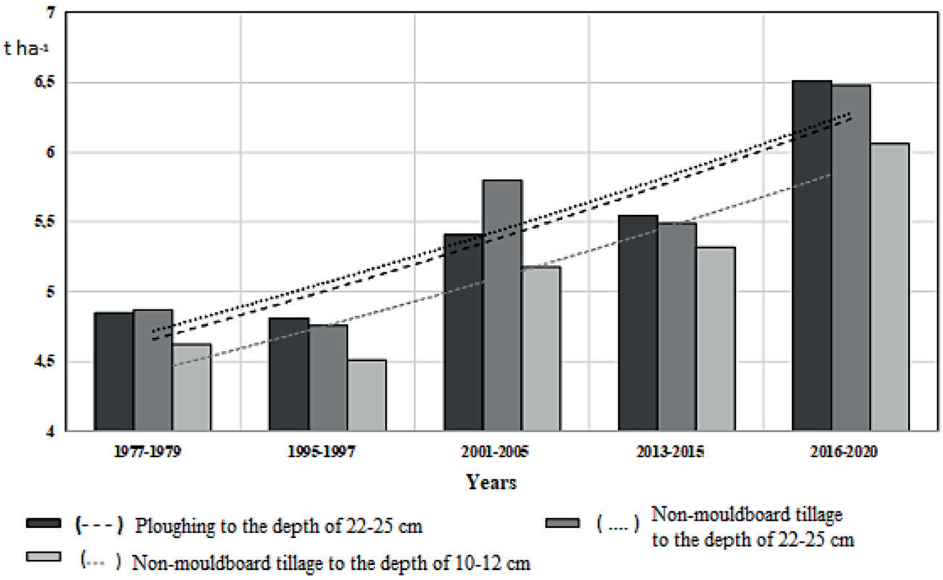

Figure 1. Dynamics of the grain crop yields in the agrocenosis of a 5-field grain-row crop rotation with perennial grasses in 1977–2020

with increased biochemical soil processes. In the chernozem layer of 0–20 cm, the activity of bacteria that absorb mineral nitrogen and enhance the activity of ammonifiers decreases.

At the same time, the number of microorganisms involved in the processes of mineralisation decreases and the amount of fungal microflora increases (Demydenko and Tonkha, 2014; Demydenko, 2021). The ratio of the number of microorganisms decomposing the organic forms of nitrogen and assimilating its mineral forms during ploughing is 1:2.0, but during non-mouldboard and surface treatment – 1:2.9 and 1–2.3, respectively. The largest number of heterotrophs was found during non-mouldboard shallow tillage, and microorganisms assimilating mineral forms of nitrogen – during non-mouldboard deep tillage in a layer of 0–20 cm. The long-term implementation of non-mouldboard tillage contributed to the fact that in the 0–20 cm layer of typical chernozem, the accumulation of the total humus was the highest due to the fact that the biogenicity of chernozem was the greatest, and at the level of a strong correlation determined the amount of assimilators of mineral nitrogen compounds (R = 0.90–0.96) with a decrease in the value of hydrolytic acidity. An inverse strong correlation was found between the decomposers of the organic nitrogen compounds and the content of mineral nitrogen compounds (NO_3 + NH_4). The use of non-mouldboard deep tillage helps to reduce mineralisation processes and increase humus accumulation.

One of the indicators of the efficiency of the fertility of a typical chernozem is the content of labile organic substances in the soil, which are involved in the formation of agrophysical properties that determine the dynamics of the soil formation and the material for the creation of stable humic substances. The smallest amount of labile organic humus compounds was found in the ploughing options, while with deep non-mouldboard tillage, both with and without fertilisation, the content of labile humic substances was close to the content with long-term maintenance of chernozem in the fallow state, which indicates the approach of soil formation processes with no ploughing to natural soil formation. Not only a separate assessment of the amount of humus and organic labile substances is important in the growth of the total humus content, but also their ratio. The ratio of carbon of the labile humus to carbon of humus during non-mouldboard treatment had its own characteristics and advantages compared to ploughing. Against the fertiliser background, the percentage of the labile humus of the total humus was 4.4–25.1%, which is 1.16–1.66 times higher than the unfertilised background. When ploughing on a fertilised background, the percentage of the labile humus was 2.2–3.0%, which is 2.0–8.5 times less compared to non-mouldboard tillage. A more efficient accumulation of the total humus, regardless of the treatment system, was found during the period of manure application, as evidenced by the ratio of the labile humus to its total content. During ploughing, the percentage of the labile humus was generally 6.1–9.6%, and, on average, in the 0-layer of typical chernozem 7.5%. With deep tillage, the percentage of the labile humus reached 7.5–10% (in 0–30 cm – 9.03%), which is 1.20 times higher than with ploughing. In shallow non-mouldboard tillage, the percentage of the labile humus from the content of the total humus is 4.6–10.6%, on average – 7.3%, which was at the ploughing level. Compared to the period of introducing by-products as organic fertilisers during ploughing, the percentage of the labile humus was halved; with non-mouldboard tillage, it remained at the level of 9.7%, and with the surface tillage it increased to 8.97%, on average, for 0–30 cm of the soil layer. Regardless of the type of organic fertilisers, the highest percentage of the labile humus was in the 0–10 cm soil layer during non-mouldboard and surface treatment: 10.0–16.6% and 19.8–20.0% when using by-products. During ploughing, the percentage of the labile humus in the 0–10 cm layer of chernozem was 6.9% and 2.0%, respectively. The established regularity should be considered as a positive phenomenon, since the non-mouldboard processing creates optimal conditions for ensuring the processes of humification and humus accumulation, as evidenced by the established positive dynamics of the total humus over the period of research.

In non-mouldboard shallow tillage, the hydrogen-accumulative process of secondary carbonisation of chernozems or the phenomenon of secondary accumulation of $CaCO_3$ in the profile of chernozems is restored due to increased hydrophilisation of the soil conditions and typical chernozem approaches to its properties of the surface boiling [40]. In addition, the relationship between the content of carbonates and the content of ammonium and nitrate nitrogen is established at the level of inverse correlation, while during plowing and deep non-mouldboard tillage, dependence is established at the level of close inverse correlation. During ploughing, the carbonates boil up at a depth below 70 cm ($CaCO_3$ content 0.01–0.42%), while deep tillage without mouldboard – at a depth of 50–55 cm (the carbonate content 0.04–0.75%). Besides, the entire humus horizon of chernozem is involved in the active turnover of nutrients and in the process of the humus formation. During surface treatment, the carbonate effervescence line is located 15–25 cm from the surface of the chernozem, and the carbonate content increases to 0.35–1.61%. Besides, exchangeable acidity acquires a slightly alkaline pH (pHsalt> 7.0), which blocks the mobile form of phosphates and exchangeable potassium at their high total content in the humus horizon. There is a process of differentiation of the humus horizon according to the components of potential fertility, and the preservative effect of $CaCO_3$ upon the realisation of potential fertility through its efficient form increases during ploughing and deep non-mouldboard loosening, and sharply decreases in shallow subsurface loosening, which reduces the productivity of the grain crops for the entire period of the research.

CONCLUSIONS

In systematic ploughing, the dynamics of the total humus content in the period 1975–1995 followed an upward trend, and, after 1995, a downward trend with a steady increase in the yield of the grain crops in a 5-field crop rotation. The growth of the humus content in the period 1975–1995. amounted to: +0.001% annually, and in the subsequent years, dehumification was -0.0048–0.008% annually. In the case of deep non-mouldboard tillage, the dynamics of the total humus followed a growing trend against the background of an increase in the yield of the grain crops, which for 38–40 years from the start of the research was equal to the yield during ploughing. During the period of manure application, the rates of humus reproduction during non-mouldboard tillage were more efficient: +0.013% (0–30 cm) of soil annually, and when manure was replaced with by-products, as an organic fertiliser, in the first years they acquired negative values, but in the 40th year of studies, accumulation of humus reached +0.0063% (0–20 cm) and +0.0013% (20–30 cm) annually. In the case of shallow non-mouldboard tillage, the growth trends in the humus content in the 0–20 cm layer of chernozem were increasing, but in the 20–30 cm layer of soil, it went down. The grain yield growth followed an increasing trend, but at a significantly lower level, compared to deep tillage. Accumulation of humus over 15 years of research (the period of manure application) was +0.014% (0–20 cm) and +0.003% (20–30 cm) annually. The replacement of manure with by-products increased the differentiation in terms of the humus content in the 0–30 cm soil layer: +0.0013% (0–20 cm) and -0.0033% (20–30 cm) annually. The accumulation of total humus relative to plowing in the 40th year of research with deep non-mouldboard tillage was

+0.0028%; at shallow non-mouldboard +0.0005%. In the first case, the humus enrichment occurred in the 0–30 cm layer of chernozem (80% in the soil layer of 0–20 cm and 20% in the soil layer of 20–30 cm), and with shallow tillage, the humus accumulation takes place in the 0–20 cm soil layer. In the case of deep non-mouldboard tillage, the heterogeneity of the structure of the cultivated layer of chernozem acquired an optimal manifestation, while with shallow treatment an excessive manifestation of differentiation occurred, which, ultimately, limited the manifestation of the productivity of the crop rotation agrocenoses in terms of the grain crop yields.

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