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HUMUS STATE OF CHERNOZEM AT DIFFERENT WAYS OF TILLAGE IN THE AGROSYSTEMS OF THE LEFT-BANK FOREST STEPPE OF UKRAINE

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Aim. To demonstrate the long-term effect of different ways of tillage of typical low-humus chernozem on the change in humus content and composition and the direction of transformation processes of organic fertilizers. To study the changes in the structure of energy reserves in group and fractional composition of humus in typical low-humus light-loamy chernozem of the Forest-Steppe of Ukraine. **Methods**. Field, laboratory, microbiological, computational, mathematical and statistical. **Results.** It was determined that in conditions of long-term subsurface tillage the most efficient humus accumulation occurs in the 0–20 cm layer of chernozem with simultaneous increase in its content in the lower part of the processed layer without any accumulation differentiation. Surface tillage leads to expressed differentiation in humus accumulation in the 0–20 cm layer of soil (0.005 % per year). When 6 t/ha of humus are replaced by 7 t/ha of by-products the intensity of humus accumulation is decreasing regardless of the way of tillage, but humus accumulation was found to be the most efficient for subsurface tillage. The application of subsurface tillage leads to the increase in the ratio of C_{HA} : C_{FA}, which is conditioned by the increase in the humification of plant remains of by-products in the 0–20 cm layer of soil by 110–112 % – for subsurface tillage, and by 105 % – for surface tillage. **Conclusions**. It was established that systematic subsurface tillage of typical chernozem of the Left-Bank Forest-Steppe of Ukraine leads to the structuring both of the total reserves of energy C_{org}, and its quality content, aimed at the increase in the intensity of the processes of humification and accumulation of organic carbon, and the decrease in mineralization. The ratio of energy reserves C_{org} of humic acids to fulvic acids in the 0–30 cm layer of chernozem is 1.85–1.87 regardless of the way of tillage, which testifies to the repeatability of humus accumulation, but the total reserves of energy C_{org} was higher for subsurface tillage (+ 31 Teracalorie/ha) compared to deep ploughing. As for the surface tillage, the energy enrichment was at the level of deep ploughing.

Keywords: humus, humification depth, subsurface tillage, bioactive humus, energy reserves in humus.
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INTRODUCTION

Insufficient introduction of organic fertilizers, absence of manure on farms and its replacement with by-products as well as application of intensive ways of tillage led to considerable increase in the load on humus in the process of agricultural production, due to which the tempo of its mineralization increased rapidly. It is disturbing that dehumification processes have widely spread among ecologically stable soils, extremely valuable for agricultural production, such as typical low-humus chernozem of the Left-Bank Forest-Steppe of Ukraine [1–3]. The urgency of the issue of humus restoration is enhanced due to insufficient compensation of mineralization loss of organic matter in modern agrosystems and the necessity of further restoration of soil fertility – the most important condition of comprehensive intensification of agricultural production. Experience has demonstrated that only soil-protecting tillage of chernozem creates the most favorable conditions for humification of organic fertilizers compared to deep ploughing and has the highest stabilizing effect on the productivity of agrosystems [4, 5].

The issue of organic carbon circulation has been the subject of a considerable number of scientific studies [5–7], including fundamental ones [8–13]. Increased interest to the study of carbon circulation problems is also observed in foreign publications [14–19]. At present the problem of the formation of organic carbon reserves and the changes in its quality and energy statuses in agrosystems, especially while applying different ways of tillage, is yet to be elucidated, it requires additional analysis both from agroecological and agronomic standpoint to define the ways of increasing potential fertility of typical chernozem. Intensive tillage leads to the decrease in the content of organic carbon on large areas, affecting its flow and circulation in the above-ground cycle, which is accompanied with the decrease in the level of soil organic compounds [13, 20, 21] and the components of group and fractional composition of humus in typical chernozem of agrosystems of the Left-Bank Forest-Steppe of Ukraine.

The aim of the work was to study long-term effect of different ways of tillage for typical low-humus chernozem on the change in the content and composition of humus and the direction of transformation processes for organic fertilizers as well as to analyze the change in the status of energy reserves in the structure of group and fractional composition of humus in typical low-humus light-loamy chernozem in agrosystems of the Left-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study was conducted in conditions of the central part of the Left-Bank Forest-Steppe of Ukraine during the long-term (over 36 years) permanent experiment of Drabiv experimental field of the Cherkasy State Experimental Station of NSC "Institute of Agriculture of NAAS". The study was conducted on typical heavy loam, light clay, low-humus chernozem with the humus content of 3.8–4.2 %, the content of mobile phosphorus of 12–14 mg per 100 g of soil and mobile potassium – 8–10 mg per 100 g of soil, pH_{H_2O} = 6.8–7.0. The long-term (1995–2010) effect of different ways of tillage on humus state of chernozem was studied in a short-term field rotation: peas–winter wheat–sugar beets–corn–corn. The determination was conducted on the field of winter wheat. The ways of soil cultivation were as follows: different depth ploughing for 22–25 cm; subsurface tillage for 22–25 cm, surface tillage for 10–12 cm. The fertilization system, a kilogram of active substance per 1 ha of field rotation: 6 t/ha of humus and 7 t/ha of by-products + $N_{62}P_{66}K_{82}$. The indices of humus condition (IHC) were calculated according to Orlov [22]. The soil biological surveys were conducted in 0–20 cm layer of soil. The selection, processing and storing of soil to study the aerobic microbiological processes in laboratory conditions were conducted according to DSTU ISO 10381–6–2001. Different groups of microorganisms were studied by microbiological analysis via cultivation of soil suspension on dense culture media. The meat-peptone agar (MPA) was used to study the total number of microorganisms, decomposing nitrogen-containing organic substances; the starch-and-ammonia agar – for microorganisms, assimilating mineral forms of nitrogen; starvation agar – for the number of oligotrophs, and Ashby medium – for the number of oligonitrophils. The method of Zvyagintsev [23] was used to estimate the colonies of microorganisms in soil and to determine the composition of the medium. The energy reserves C_{org} in fractions of group and fractional composition was estimated using the improved method [24]. The permanent field study was conducted according to Dospekhov [25].

RESULTS AND DISCUSSION

In 1995 (the end period for the introduction of 6 t/ha of manure) the content of total humus in the 0–20 cm layer of chernozem was 3.98 % for deep ploughing, 4.02 % for subsurface tillage, and 3.98 % for surface tillage. The determination of these indices in 2010 (the period of applying 7 t/ha of by-products) demonstrated that with deep ploughing the humus content decreased by 0.13 %, with subsurface tillage – by 0.10 %, and with surface tillage – by 0.09 %. Compared to the beginning of studies the humus content decreased by 0.11 % with ploughing, increased by 0.06 % with subsurface tillage, and increased by 0.17 % with surface tillage. In 2010 the content of total humus in the 20–40 cm layer of soil increased by 0.02, 0.03 and 0.01 % with deep ploughing and subsurface tillage, respectively (in 1995 – 3.73; 3.74 and 3.42 % compared to the mentioned depth of the arable layer). Compared to 1976 [26] the humus reserves increased by 0.13 and 0.10 % with ploughing and subsurface tillage and decreased by 0.15 % with surface tillage (Fig. 1).

During 1995–2010 the humus content in the 0–40 cm layer of soil decreased by 0.04–0.06 % regard-

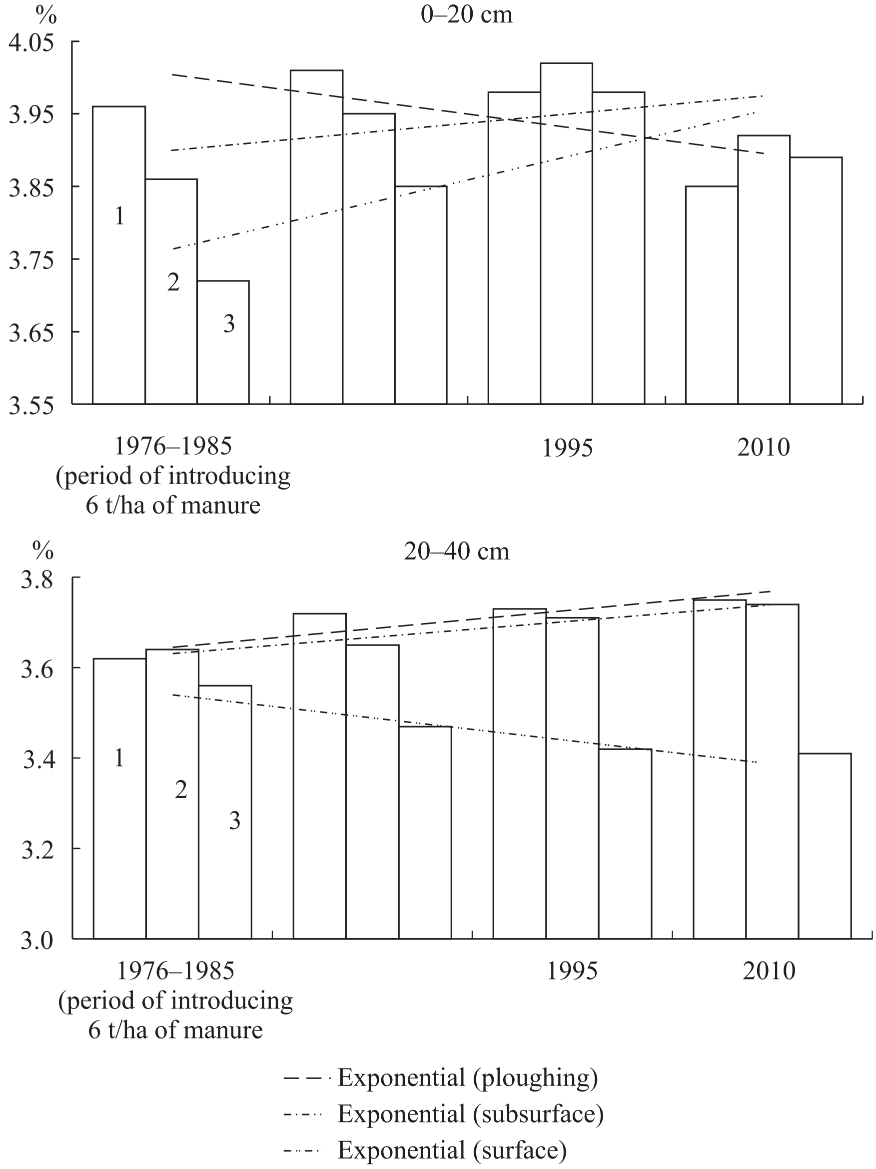

Fig. 1. The dynamics in the change of total humus content depending on the way of tillage (1 – deep ploughing; 2 – subsurface tillage; 3 – surface tillage) of typical low-humus chernozem in 5-course grain-hoed crop rotation: until 1985 – 6 t/ha of manure + $N_{56}P_{52}K_{64}$; 1996–2010 – 7 t/ha of straw + $N_{64}P_{64}K_{81}$. $HIP_{0.05}$: 0–20 cm – 0.056 %, 20–40 cm – 0.045 %; 0–40 cm – 0.03 %

less of the way of tillage; compared to the beginning of the study it increased by 0.01, 0.08 and 0.01 % respectively. The differentiation process regarding accumulation was registered during the systematic surface tillage for 34 years: in the 0–20 cm layer of chernozem humus accumulated at the level of 0.005 % per year, whereas in the 20–40 cm soil layer its content decreased by 0.004 % per year, while the difference in the humus content between soil layers of 0–20 and 20–40 cm in 2010 was 0.48 % or 115 % less. This phenomenon was not observed for subsurface tillage and deep ploughing.

Long-term application of subsurface tillage is the most relevant reason of the increase in the ratio of energy reserves C_{org} of humic acids (HA) to fulvic acids (FA) $C_{HA} : C_{FA}$, which is conditioned by the application of organic fertilizers and increased humification of plant remains of by-products. For instance, this ratio increased by 110–112 % in the 0–20 cm soil layer with subsurface tillage, and by 105 % – with surface tillage.

According to Boyko [26], the ratio of $C_{HA} : C_{FA}$ in the experiment with ploughing in 1994 was 1.18–1.24, with subsurface tillage – 1.18–1.32, and with surface tillage – 1.15–1.28, and 1.21, 1.27 and 1.22 respective-

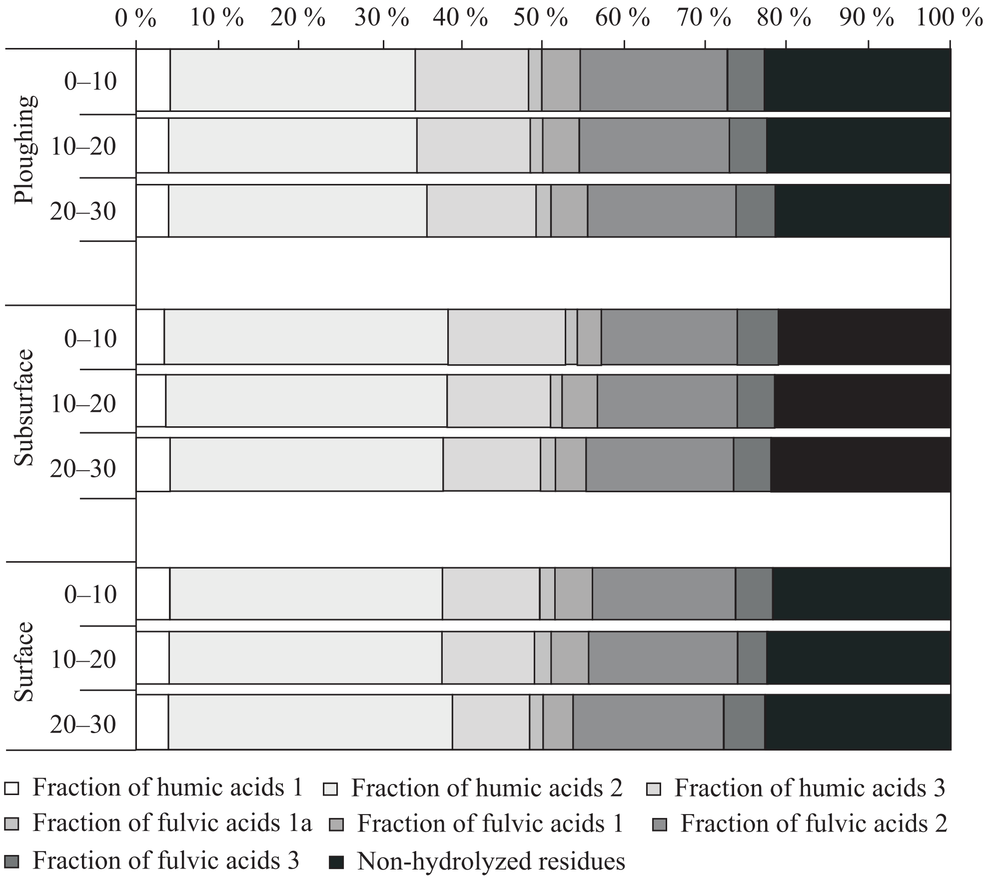

Fig. 2. The long-term effect of different ways of tillage for typical low-humus chernozem on group and fractional composition of humus

ly compared to the tillage of the 0−30 cm soil layer. In 2010 the ratio C_{HA} : C_{FA} increased 1.37 times with deep ploughing, 1.43 times with subsurface tillage, and 1.41 times with surface tillage which testifies to the formation of better conditions of humification during subsurface tillage when there is considerable improvement of soil and fraction composition of humus. Long-term application of different ways of tillage of typical chernozem conditions the changes both in the content of total humus and in its quality composition. The estimation of the content of labile bioactive humus of fractions FA-1a, FA-1 and HA-1 demonstrated the de-crease in the formation of the latter by 113 % under the effect of systematic subsurface tillage in the 0–30 cm soil layer compared to deep ploughing and surface tillage. The content of fractions of stable bioactive humus (HA-2, FA-2) with subsurface and surface tillage increased by 104–106 % and by 106 % with surface tillage in the 20–30 cm soil layer. During subsurface and surface tillage the content of fractions of stable bioactive humus exceeded 50 %, whereas with ploughing it was less (Fig. 2).

The index of relative motility of humus (I_h) was 1.19 times higher for systematic ploughing in the 0–30 cm soil layer compared to the subsurface tillage, and 1.09 times higher for surface tillage. The estimation of layers demonstrated that I_h value for ploughing in the 0–10 cm soil layer was 1.4 times higher, and in the 10–20 cm layer – 1.18 times higher compared to systematic subsurface tillage, and it increased 1.19 times compared to surface tillage in the 20–30 cm soil layer. Therefore, compared to ploughing the process of involving the fractions of labile bioactive humus to the fractions of stable bioactive humus is the most intensive for deep subsurface tillage. With surface tillage the mentioned processes are weaker in the 0–20 cm layer, and at the level, similar to that for subsurface tillage, – in the 20–30 cm soil layer (Table 1, Fig. 3).

With systematic application of subsurface tillage the highest level of HA-3 humus fractions was revealed in the 0–10 cm soil layer, whereas their content decreases deeper down and is lower compared to ploughing. The concentration of insoluble residue was 21.6–22.3 % regardless of the way of chernozem tillage. A

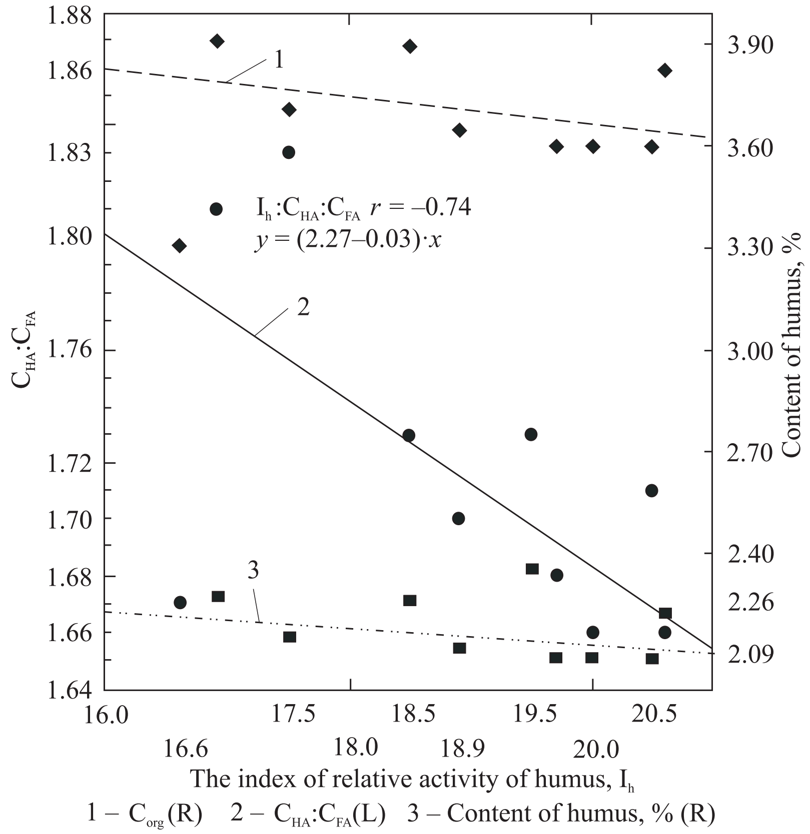

Fig. 3. The dependence between the humus content, the humification depth and the index of relative activity of humus substances of typical low-humus light-loamy chernozem

Table 1. The long-term effect of different ways of tillage on humus state of the 0–30 cm layer of typical low-humus chernozem.

Depth, cm	N_{total}	C_{org}	Humus, %	*I_h	$C_{HA}:C_{FA}$
Ploughing for					
0–10	0.21	2.22	3.82	0.21	1.66
10–20	0.21	2.09	3.60	0.19	1.65
20–30	0.20	1.96	3.38	0.19	1.68
0–30	0.21	2.09	3.60	0.21	1.66
Subsurface tillage for					
0–10	0.23	2.39	4.12	0.15	1.86
10–20	0.22	2.26	3.90	0.19	1.73
20–30	0.22	2.15	3.71	0.18	1.83
0–30	0.22	2.27	3.91	0.17	1.81
Surface tillage for					
0–10	0.23	2.35	4.04	0.19	1.73
10–20	0.21	2.09	3.60	0.20	1.71
20–30	0.19	1.92	3.31	0.17	1.67
0–30	0.21	2.12	3.65	0.18	1.71

*Note. I_h – index of relative motility of humus.

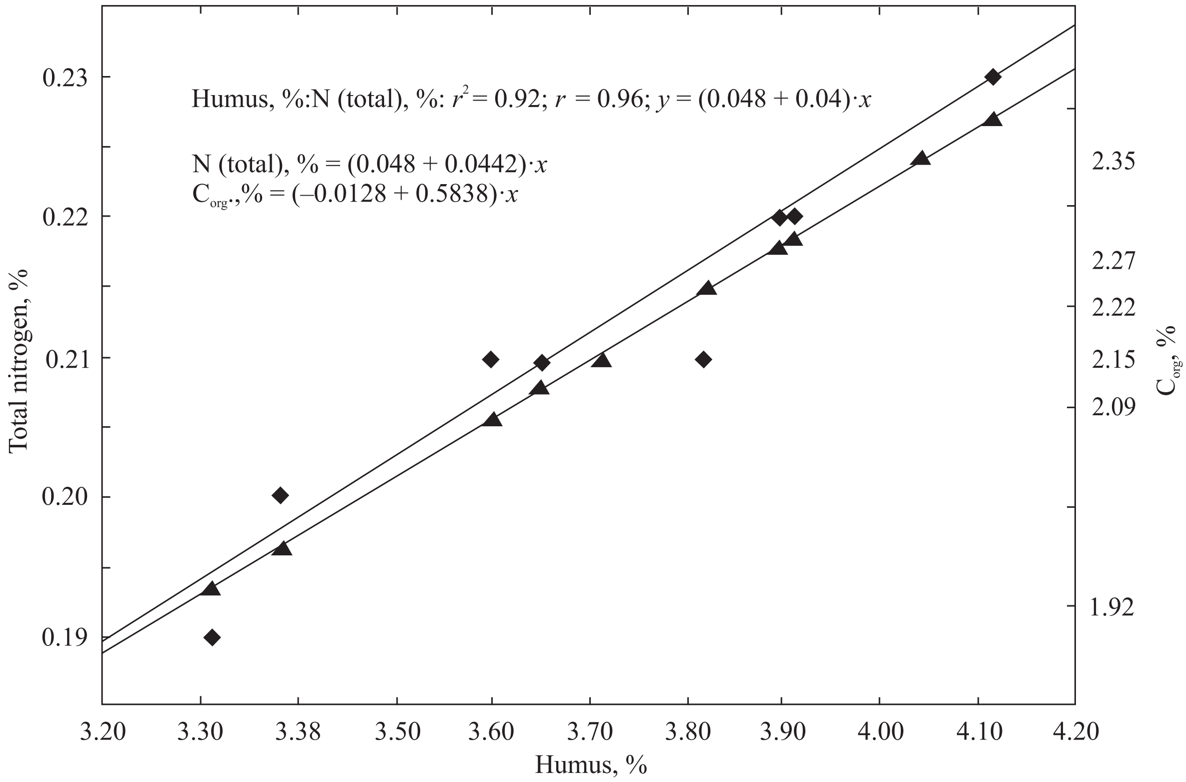

Fig. 4. The dependence between the content of humus, carbon and total nitrogen in typical low-humus light-loamy chernozem

weak tendency towards its decrease was revealed for subsurface tillage in the 0–30 cm of soil layer (21.4–21.9 %), for ploughing – in the 20–30 cm soil layer (21.5 %) and for surface tillage – in the 0–10 cm soil layer (21.7 %).

The mentioned changes testify to the fact that with subsurface tillage the labile bioactive humus is involved in the composition of fractions of stable bioactive humus most intensively. There is also the differentiation of the processed chernozem layer by the content of HA-3. Long-term application of the surface tillage has considerable effect on the level of fractions regarding bioinert humus (HA-3). For instance, the content of the mentioned fraction was 1.23 less in the 0–30 cm soil layer compared to ploughing and 1.18 times less compared to subsurface tillage.

With subsurface tillage the direct correlation (R = = (0.62–0.67) ± 0.03) was found between the ratio C_{HA}:C_{FA} and the humus content, whereas there was direct strong correlation (R = 0.59 ± 0.02) between the ratio C_{HA}:C_{FA} and total nitrogen content. The correlation became reverse and strong with systematic ploughing. The reverse correlation at the level of strong correlation was found between the indices of I_h, the content of total nitrogen and C_{FA} and humus content in conditions of subsurface tillage, whereas it was direct for ploughing and surface tillage.

The dependence between the content of total nitrogen and humus in typical chernozem is at the level of direct strong correlation, which indicates the reserves of organic carbon in soil (Fig. 4).

It was determined that biogenicity was the highest for subsurface tillage in the 0–20 cm soil layer compared to ploughing and surface tillage. Further studies demonstrated direct strong correlation between the humus content and biogenicity level (R = 0.82 ± 0.03; R^2 = = 0.67). It explains the highest content of humus in the 0–20 cm soil layer with subsurface tillage: 3.92 %, which is 0.07 % higher compared to ploughing and 0.03 % higher compared to the surface tillage.

It was revealed that there is direct strong correlation between the biogenicity level in the 0–20 cm chernozem layer and the humification depth (C_{HA} : C_{FA}) – (R = 0.88 ± 0.03, R^2 = 0.77), which explains the enrichment with humus and the change in the depth of humification with subsurface tillage compared to ploughing and shallow subsurface tillage. The direct correlation (R = 0.81 ± 0.03) was found between the fractions of stable bioactive humus and biogenicity, and the reverse strong correlation (R = –0.93 ± 0.03) – between the

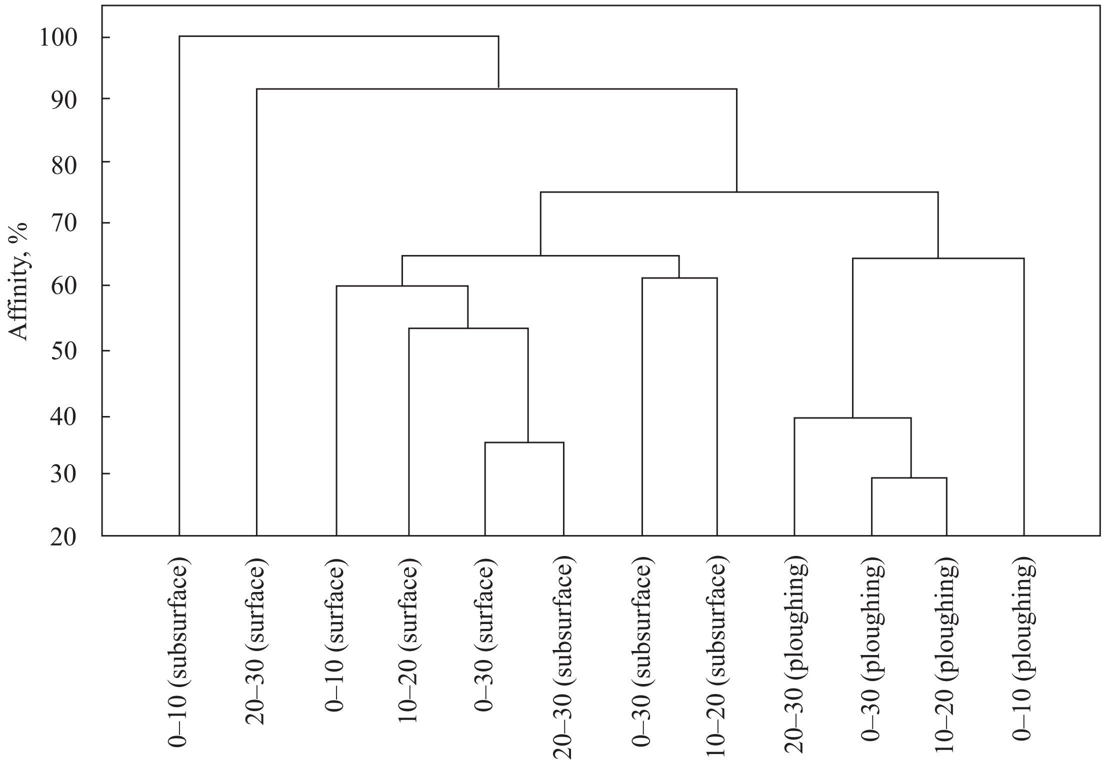

Fig. 5. The effect of different ways of tillage for typical low-humus chernozem on the similarity level of humus horizon according to the set of properties

former and I_h. The humification depth is related to the number of microorganisms − decomposers of organic compounds of nitrogen ($R = -0.97 \pm 0.03$) and microorganisms − assimilators of mineral compounds of nitrogen ($R = 0.98 \pm 0.01$), as well as to the content of nitrogen compounds, which are easily hydrolyzed ($R = 0.95 \pm 0.02$). It was established that with subsurface tillage the highest indices of phosphate-mobilizing and nitrogen-providing properties of the 0–20 cm soil layer are conditioned by increased indices of the humification depth of organic matter in humus.

The dendrogram (Fig. 5) of the affinity between separate soil layers at different ways of tillage demonstrates that in terms of the complex of indices of group and fraction composition of humus (17 indices) and biogenicity (8 indices), with ploughing the soil layers of 0–10, 10–20 and 20–30 cm are united in separate integrated clusters, whereas with subsurface and surface tillage these horizons are united into separate clusters, remotely related to quality indices for ploughing at the level of 75 %.

In terms of quality there are differences for the 0–10 cm soil layer at subsurface tillage and the 20–30 cm soil layer at the surface tillage, which is related to specific conditions of biogenicity and the direction of humus

Table 2. The long-term (34 years) effect of different ways of tillage on humus energy reserves in the 0–30 cm layer of typical low-humus light-loamy chernozem

Depth, cm	Humus energy reserves Petacalorie/ha	Re-distribution within 0–30 cm soil layer, %	Increase compared to ploughing, %
Ploughing for			
0–10	32.8	30.7	100
10–30	74.2	69.3	100
0–30	107	100	100
Subsurface tillage for			
0–10	46.8	35.4	143
10–30	86.0	64.6	116
0–30	132.8	100	124
Surface tillage for			
0–10	42.2	35.8	129
10–30	75.6	64.2	102
0–30	117.8	100	110

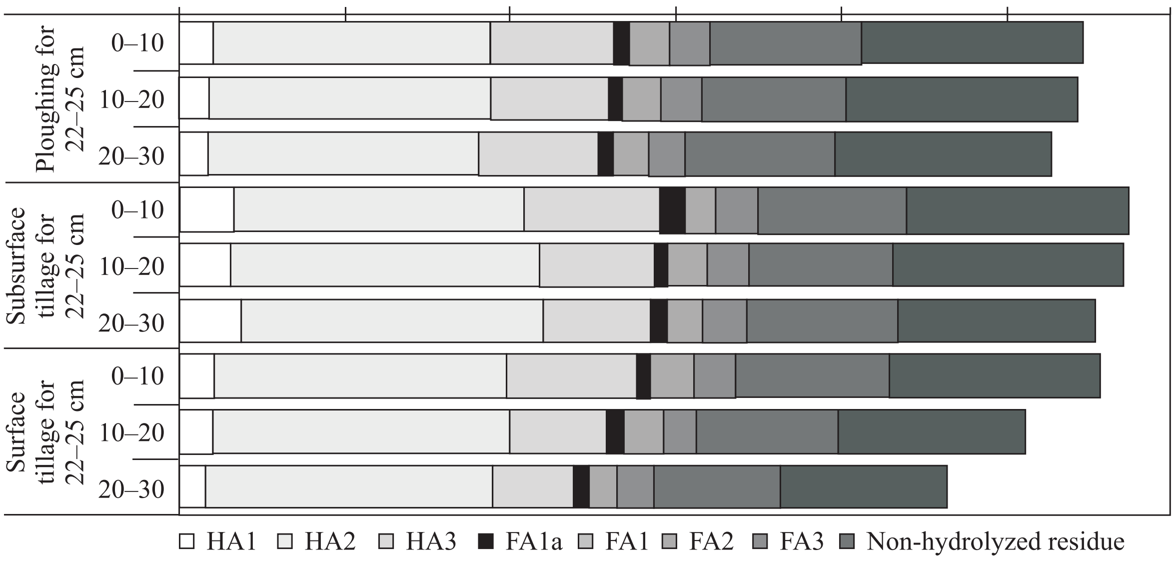

Fig. 6. The long-term effect of different ways of tillage on the reserves of C_{org} in different fractions of humus in typical low-humus light-loamy chernozem of the Left-Bank Forest-Steppe of Ukraine

accumulation. Overall, in terms of quality and quantity composition of humus and biogenicity, the condition of the 0–30 cm soil layer depends on the way of tillage: the dendrogram (Fig. 5) of the affinity degree demonstrates that in terms of the quality composition the latter is 65 % for parts of the processed chernozem layer, and the distance is 90–92 %.

With subsurface tillage the humus energy reserves in the 0–30 cm soil layer increased by 124 % compared to ploughing, and with surface tillage – by 110 %. With subsurface tillage there was the increase by 143 % in the humus energy reserves in the 0–10 cm soil layer, and with the surface tillage – by 129 %. The energy reserves in the 10–30 cm soil layer increased by 116 % with the subsurface tillage, and by 102 % – with surface tillage (Fig. 6, Table 2).

The long-term application of different ways of tillage affects the reserves of organic carbon (C_{org}) in the 0–30 cm chernozem layer. Thus, the highest values were found for subsurface tillage – 83.0 t/ha. With ploughing the reserves were 3.4 t/ha less, and with surface tillage – 6.4 t/ha less ($HIP_{0.05}$ = 3.1 t/ha). With subsurface and surface tillage the 0–10 cm soil layer accumulates 34.0 and 36.4 % from the total reserves of organic carbon, and deeper down its reserves decrease to 30 % with surface tillage, whereas with ploughing they become even along the whole arable layer of chernozem Fig. 6).

The carbon reserves in the 0–30 cm chernozem layer turned out to be higher with deep subsurface tillage (43.4 t/ha), whereas with ploughing and surface tillage it was 1.08–1.1 times less. The highest amount of organic carbon of HA is located in the 0–10 cm chernozem layer with subsurface tillage (15.2 t/ha). With ploughing the reserves of C_{HA} decrease 1.15-fold, and with surface tillage – 1.1-fold. With subsurface tillage the carbon reserves in the 0–30 cm chernozem layer are up to 22.1 t/ha, whereas with ploughing and surface tillage they tend to decrease – 20.9 t/ha ($HIP_{0.05}$ = = 1.12 t/ha).

The estimation of the reserves of C_{org} of the most active part of humus (HA-1 + FA-(1+1a)) demonstrated that its accumulation in the 0−30 cm soil layer with subsurface tillage is 7.76 t/ha. With ploughing the most intense accumulation of organic carbon of the mentioned fractions occurs in the 10–30 cm chernozem layer, whereas with surface tillage – in the 0–20 cm soil layer: 5.1 and 5.28 t/ha respectively. With surface tillage the content of C_{org} of active fractions of humus in the 20–30 cm soil layer was found to be the lowest: 2.05 t/ha which is 1.28 times less compared to subsurface tillage and 1.17 times less compared to ploughing (Fig. 6).

The reserves of C_{org} of the active part of humus compared to its total accumulation with ploughing was 9.33−9.94 %, with subsurface tillage – 8.95−10.94 %, with surface tillage – 9.03−9.91 %, and compared to the total reserves of organic carbon in HA and FA with subsurface tillage it decreased in the 0−20 cm chernozem layer down to 11.5−11.6 %, in the 0−30 cm layer it was 11.8 %, whereas with surface tillage and ploughing the reserves of C_{org} of active fractions increased 1.05−1.06-fold. In the 0−30 cm soil layer the reserves of C_{org} reached the values of 12.35−12.45 %. The mentioned changes are related to the formation of the reserves of C_{org} of humus of the non-hydrolyzed remains, the accumulation of which was the highest with subsurface tillage (19.32 t/ha) whereas with ploughing and surface tillage the reserves of this fraction decreased by 1.41 and 1.98 t/ha respectively. With subsurface tillage the reserves of organic carbon in the insoluble remains were the highest in the 20–30 cm soil layer, and with surface tillage – in the 0–10 cm soil layer.

The indices of humus condition (IHC) – the ratio between the reserves of C_{HA} to the reserves of C_{FA} – reflect bioclimatic conditions of organic carbon accumulation with different ways of tillage of typical chernozem. It was established that regardless of the way of tillage a fulvic-humate type of humus with IHC = 1.85 is formed in the 0–30 cm chernozem layer. With ploughing IHC = 1.91, whereas with subsurface tillage IHC = = 1.85−1.86. With subsurface tillage the value of $C_{HA} : C_{FA} > 1.9 : 1$ was in the 10–20 cm soil layer with deep subsurface tillage and in the 20–30 cm soil layer – with shallow subsurface tillage.

It was determined that the way of tillage does not have any significant effect on the humification degree of organic substance – the ratio of the reserves of C_{org} of HA to the reserves of C_{org} in humus (HC) was high (HC > 40 %) in the processed chernozem layer (0−30 cm) regardless of tillage. With ploughing HC was 49.5 %, with subsurface tillage − HC = 51 %, with surface tillage − HC = 52 %.

The most typical fraction in the composition of HA of chernozem soil is HA-2, related to calcium. Regardless of tillage the sum of carbon of HA-2 is very high (> 80 %): with ploughing – 92–93 %, with subsurface tillage − 92–94 %, with surface tillage − 92–93 %. The reserves of organic carbon of humic acids, closely connected to the reserves of C_{org} of HA in the 0–30 cm soil layer, depend on the way of chernozem tillage: with ploughing it is 26.9−28.7 % from the total reserves of C_{org} of HA, whereas with subsurface tillage – 25.6 %, and with surface tillage – 24.4 %. The percentage of organic carbon reserves of closely connected HA-2 increases with depth in the 20–30 cm soil layer up to 28.5–29. %, *i. e.* the ratio differentiation is becoming more expressed with the minimization of tillage.

The share of the reserves of C_{org} of HA-1 in the total accumulation of carbon in HA with subsurface and surface tillage in the 0−30 cm chernozem layer is 6.7−7.9 %, and with ploughing – 7.0−7.8 %. With surface tillage the reserves of carbon of HA-1 increase in the surface layers of chernozem (0–20 cm), whereas with subsurface tillage – in deeper ones. With ploughing the reserves of organic carbon are even along all the layers of processed chernozem. The estimation of the relative motility index for reserves of C_{org} ($RMI_{(Corg)}$, %) as the ratio of carbon reserves of HA-1 + FA-(1 + + 1a) to carbon reserves of HA-2 + FA-2 demonstrated that with ploughing in the 0−30 cm layer $RMI_{(Corg)}$ is 26.79 %, whereas with subsurface tillage $RMI_{(Corg)}$= = 25.89 %. It was found that with subsurface and surface tillage the relative motility index of organic carbon is the highest in the 0−10 cm soil layer ($RMI_{(Corg)}$= = 26.35 and $RMI_{(Corg)}$= 27.3 %), and with depth its values decrease down to $RMI_{(Corg)}$= 23.5−24.8 % with subsurface tillage and $RMI_{(Corg)}$= 20.8 % with surface tillage. With ploughing the value of $RMI_{(Corg)}$ is even along the whole processed chernozem layer.

The coefficients of mineralization (Cm) of HA (Cm = 0.19–0.2) and FA (Cm = 0.1–0.13) were used to estimate the weight of organic carbon, capable of mineralization with different ways of chernozem tillage (Table 3). It was determined that regardless of the way of tillage, approximately the same weight of organic carbon of HA (2.08–2.021 t/ha) is capable of mineralization in the 0–30 cm soil layer. However, the way of chernozem tillage had some effect on the weight of C_{org} in FA: it is mineralized the least with surface tillage (2.69 t/ha) whereas with ploughing the weight of organic carbon, capable of mineralizing FA, increases 1.1-fold.

In general the share of C_{org} fraction of HA and FA, capable of mineralizing regardless of the way of tillage, was almost the same: 4.79−5.08 t/ha, and in equivalent of humus – 8.25−8.75 t/ha. The 0−10 cm chernozem layer has the highest mineralization of C_{org} of HA: 59.4−61.0 % from the total amount of organic carbon, capable of mineralization. The mineralization of C_{org} of HA decreases with depth: 27.5−30.6 % for ploughing, 30.4−31.4 % − for subsurface tillage, 30.0−32.0 % − for surface tillage, which is related to high resistance of HA to mineralization.

Vice versa, the weight of C_{org} of FA, capable of mineralization, increases with the depth, whereas it decreases in the 0–10 cm soil layer inversely to the mineralization character of HA carbon. Here the lowest indices are found for deep subsurface tillage, which should be directly related to the increase in the total reserves of C_{org} of humus in the 0−30 cm chernozem layer.

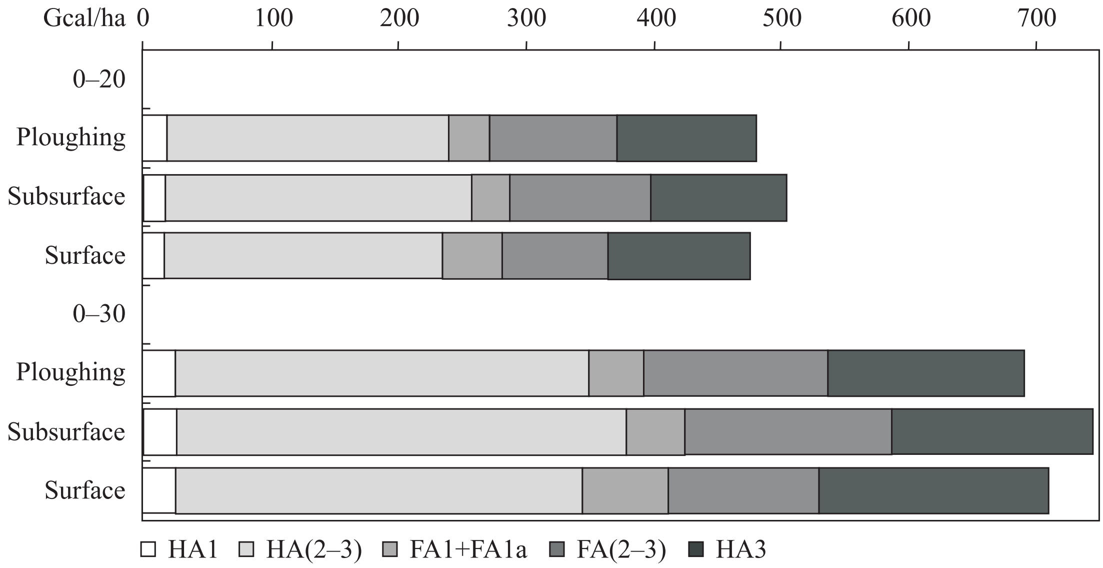

Fig. 7. The structure of energy reserves of C_{org} in components of group and fractional composition of humus depending on the way of tillage of typical low-humus chernozem

In terms of quantity for subsurface tillage the 0–30 cm chernozem layer has mineralization of 2.21 t/ha of C_{org} of HA and 2.87 t/ha of C_{org} of FA; for ploughing – 2.08 and 2.95 t/ha. Regardless of this fact the humification intensity in the 0–20 cm chernozem layer is high with subsurface tillage (about 3 % higher compared to ploughing and surface tillage). In general the highest level of humification in the processed chernozem layer was found for systematic ploughing and subsurface tillage, whereas with surface tillage the intensity of humification is 1.2–1.22 times decreased (Table 3).

The highest intensity of humification of plant remains in the 0–10 cm chernozem layer was registered for subsurface tillage, whereas with ploughing it decreased 1.29 times and with surface tillage – 1.22 times. It was established that compared to surface tillage, the intensity of humification with subsurface tillage is less decreased, and on the contrary – with ploughing the intensity of humification increases 1.38 and 1.49 times respectively compared to subsurface and surface tillage. The reason can be found in the localization of post-harvest remains and by-products in the soil layers of 0–20 cm (subsurface tillage) and 20–30 cm (ploughing).

Table 3. The effect of ways of tillage on the humification intensity of C_{org} of plant remains on the background of $N_{60}P_{88}K_{100}$ + 6–7 t/ha of by-products

Depth, cm	The way of soil preparation		
	Deep ploughing, 20–22 cm	Subsurface tillage	
		22–25 cm	10–12 cm
0–10	0.168	0.216	0.177
10–20	0.191	0.165	0.145
20–30	0.183	0.133	0.123
0–30	0.181	0.171	0.148

Using the data on the reserves of C_{org} in humus and components of group and fractional composition of humus, the structural analysis of energy reserves of humus and its components for different ways of tillage of chernozem was performed (Fig. 7). It was established that subsurface tillage leads to considerable increase in the energy in the most stable fractions (HA-(2 + 3) + + FA-(2 + 3)) of humus: comparing to ploughing (the 0–30 cm soil layer) the energy reserves of organic carbon increased by 8 % (because C_{org} of fractions FA-(2 + 3) − by 5.1 %, and fractions HA-(2 + 3) – by 2.6 %). With subsurface tillage the enrichment of the 0–30 cm soil layer with the C_{org} energy of the mentioned fractions occurs due to the energy accumulation in the upper part of the processed chernozem layer: the energy reserves increase 1.17 times compared to ploughing and are about 70 % from the total reserves in this layer, whereas with ploughing they are 63.1 %. With surface tillage the mentioned processes are weaker, but still at a much higher level, compared to ploughing. The energy reserves C_{org} of active humus fractions (HA-1, FA-

(1a + 1)) in the 0–30 cm soil layer were the highest for ploughing, whereas with subsurface and surface tillage they decreased 1.31 and 1.38 times compared to the total energy reserves in the 0–30 cm chernozem layer: with ploughing the reserves were 13.1 % against 9.6–9.8 % with subsurface tillage.

The increase in the energy reserves of organic carbon in active fractions of chernozem humus was found for ploughing, whereas with subsurface tillage the energy reserves decreased 1.35 times and 1.31 times, which testifies to excessive activation of humus for systematic ploughing, where the energy reserves C_{org} of active humus fractions increase 1.51–1.62 times compared to subsurface tillage.

The energy reserves C_{org} of the non-hydrolyzed remains in the 0–30 cm chernozem layer were 1.14–1.18 higher for ploughing, and in terms of the total energy reserves in case of ploughing C_{org} was 13.1 %, whereas with subsurface tillage – 9.6–9.8 %, which testifies to the increase in humus inactivity or its hardening. The change in the structure of C_{org} reserves in HA fractions under the impact of different ways of tillage for chernozem soil is related to the fluctuations of nitrogen content and reserves therein.

With subsurface tillage the concentration of nitrogen in the hydrolyzed part of HA and FA increases by 111 %, ammonium nitrogen – by 128 %, amide nitrogen and non-hydrolyzed residue – by 113 %, and the content of non-oxidized aromatic compounds decreases 2.57 times compared to ploughing and not deep subsurface tillage. The content of nitrogen in HA and FA fractions was 1.1 times higher with deep subsurface tillage which affected the nitrogen reserves in the mentioned humus fractions: 1.193 t/ha against 1.032 and 1.065 for ploughing and not deep subsurface tillage respectively (Table 4).

With deep subsurface tillage there was a similar increase in the reserves of nitrogen of the hydrolyzed part of HA and FA (+ 51.0 t/ha), ammonium nitrogen (+ 25.0 t/ha), amide nitrogen (+ 34 t/ha) and nitrogen of non-hydrolyzed residue (+ 278 t/ha) and the reserves of non-oxidized aromatic compounds decreased by 5 t/ha (Table 4).

With subsurface tillage the humus energy reserves in the 0–30 cm soil layer increased by 124 % compared to ploughing, and with surface tillage – by 110 %; there was the increase in the humus energy reserves by 143 % in the 0–10 cm layer with subsurface tillage and by 129 % – with surface tillage.

The most relevant indices of soil quality are biomass of microorganisms, taxonomic composition of microflora and its functional diversity. They are subject to the same regularities of dependence on ecological factors, actual for observations of macroorganisms. It means that the deterioration of ecological condition of soil is taxonomic, therefore, the functional diver-

Table 4. The content of nitrogen in the fractions of humic acids (HA) and fulvic acids (FA) depending on the long-term application of different ways of tillage for typical low-humus light-loamy chernozem

The way of tillage of soil	Nitrogen content (%) in HA and FA fractions:					
	hydrolyzed part	ammonium	amide	non-hydrolyzed residue	of non-oxidized aromatic compounds	HA + FA
Nitrogen content, %						
Deep ploughing for 22–25 cm	12.99/28.9*	3.68/8.2	9.31/20.7	18.55/41.3	0.36/0.90	44.89/100
Subsurface tillage for 22–25 cm	14.45/29.31	4.15/8.4	10.25/20.8	20.32/41.2	0.14/0.29	49.31/100
Subsurface tillage for 10–12 cm	13.0/29.1	3.69/8.3	9.27/20.8	18.36/41.1	0.33/0.74	44.65/100
Reserves, tons/ha						
Deep ploughing for 22–25 cm	299	85.0	214	426	8.0	1032
Subsurface tillage for 22–25 cm	350	100	248	492	3.0	1193
Subsurface tillage for 10–12 cm	310	88.0	221	437	9.0	1065

Note. Nitrogen content (%) in HA and FA fractions compared to the total amount.

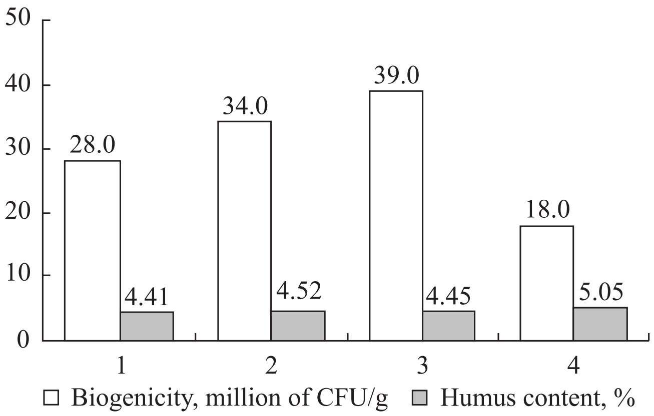

Fig. 8. The long-term effect of the ways of tillage and maintenance of chernozem on total biogenicity and content of humus in the 0–20 cm layer: 1 – ploughing for 22–25 cm; 2 – subsurface tillage for 22–25 cm; 3 – subsurface tillage for 10–12 cm; 4 – fallows for 40 years

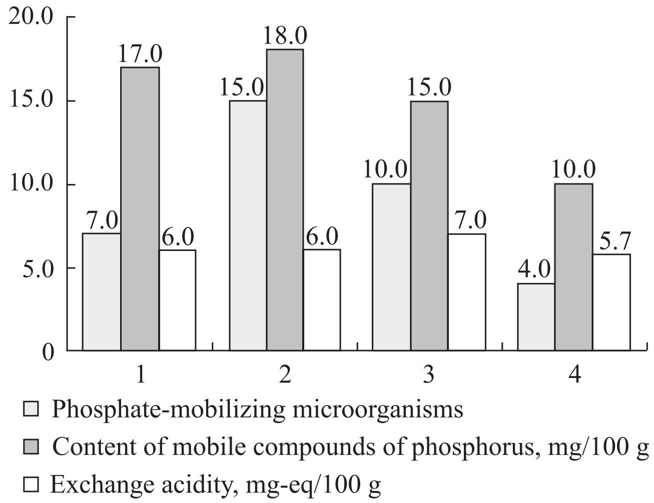

Fig. 9. The long-term effect of the ways of tillage and maintenance for chernozem on the content of mobile compounds of phosphorus, exchange acidity and amount of phosphate-mobilizing microorganisms (the 0–20 cm soil layer): 1 – ploughing for 22–25 cm; 2 – subsurface tillage for 22–25 cm; 3 – subsurface tillage for 10–12 cm; 4 – fallows for 40 years

sity of microbial grouping decreases. New systems of tillage differ from the traditional one by the fact that plant remains and fertilizers are located in the upper layer. The revolving of hunks on the soil surface leaves 10–15 % of plant remains, two-disk plowing – 30–50 %, para-ploughing – 60–70 %, subsurface tillage – 80 %. Therefore, the way of tillage determines the localization of the main mass of organic remains in the soil, which leads to differentiation by the biogenicity of soil layers. The minimization of tillage in the 0–20 cm soil layer leads to the decrease in bacteria activity, there are less actinomyces, weakly developed bacteria, consuming mineral nitrogen, but the activity of ammonifiers, nitrifiers and cellulose-decomposing organisms does not change. The minimization of tillage decreases the number of microorganisms, participating in the mineralization processes, and increases the amount of fungal microflora.

The long-term application of subsurface tillage facilitates the highest amount of humus in the 0–20 cm chernozem layer: + 0.14 %; surface tillage provides its excess by 0.03 % compared to ploughing. When fallows are maintained, there is 5.05 % of humus in the 0–20 cm soil layer, and the increase in the amount of humus, compared to ploughing, in the course of 34 years of maintaining was + 0.64 % or 0.02 % per year.

The subsurface and surface tillage of soil lead to the optimization of the level of aeration, moisturization, temperature, increase in the amount of plant remains, coming into the 0–20 cm soil layer, which enhances the biogenicity and improves the humification conditions of by-products (Fig. 8).

The content of mobile compounds of phosphorus in typical chernozem depends on the level of acidity and intensity of transformation for organophosphates and phosphatase synthesis by microorganisms (Fig. 9). The highest number of phosphate-mobilizing microorganisms and acidification of soil environment while conducting subsurface tillage promote obtaining the highest index of the content of mobile compounds of phosphorus. Close correlation ($r = 0.67$) was found between the content of mobile compounds of phosphorus and the number of phosphate-mobilizing microorganisms. The decrease in the exchange acidity and the increase in the concentration of phosphate-mobilizing microorganisms by 41 % with surface tillage compared to ploughing conditioned the decrease in the intensity of the formation of mobile compounds of phosphorus (Fig. 9).

The ratio of the number of microorganisms, decomposing organic forms of nitrogen, and the microorganisms, assimilating mineral forms of nitrogen, while maintaining fallows, is 1:1, which leads to the formation of the highest content of ammonium and nitrate nitrogen. With ploughing these indices are 1:2.2 and with subsurface and surface tillage – 1:2.8 and 1:2.3 respectively. The highest amount of heterotrophs, cultivated on MPA, was found for surface tillage, and that of microorganisms, assimilating mineral forms of nitrogen – for subsurface tillage (Fig. 10).

The biogenicity of the 0–20 cm chernozem layer at the level of strong correlation determines the number of phosphate-mobilizing microorganisms and assimilators of mineral compounds of nitrogen ($R = 0.90{-}0.96$) with the increase in the value of hydrolytic acidity. The mentioned regularity is most evident with subsurface tillage, when these parameters are optimally interrelated. With surface tillage the excessive neutralization of hydrolytic acidity leads to the decrease in the number of mobile forms of phosphorus and the decrease in the content of phosphate-mobilizing microflora (Table 5).

Strong inverse correlation was found between decomposers of organic compounds of nitrogen and the content of mineral compounds of nitrogen (NO_3 + NH_4), whereas the correlation with hydrolytic acidity was revealed to be direct. The content of mobile forms of phosphorus in soil is directly related to the presence of phosphate-mobilizing microflora, the activity of which is maximal in the pH range of 6.7–6.8, whereas the optimum of development of nitrifying microflora in soil was revealed for neutral reaction, which is more remarkable for systematic ploughing. The excessive formation of active carbonates, released from after-harvest remains and “drawn” from deeper horizons, facilitates the decrease in humus accumulation and the decrease in the content of easily hydrolysable nitrogen compounds. There is a process of “preservation” of efficient fertility contrary to the degradation processes with systematic ploughing.

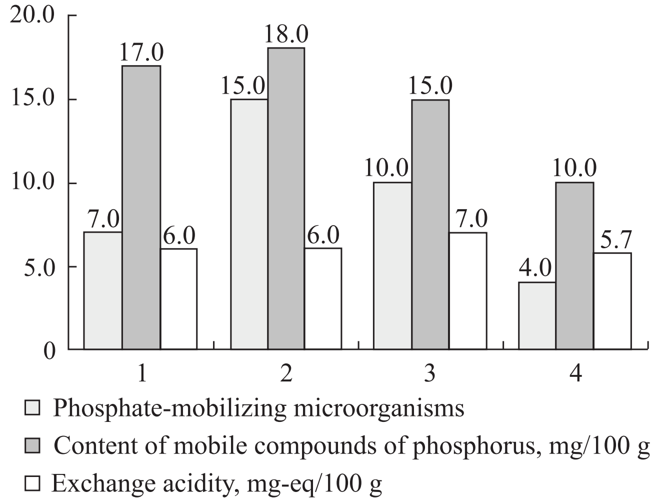

Fig. 10. The long-term effect of the ways of tillage and maintenance for chernozem on the number of decomposers of organic substances of nitrogen, assimilators of mineral forms of nitrogen and the content of ammonium and mineral nitrogen (the 0–20 cm soil layer): 1 – ploughing for 22–25 cm; 2 – subsurface tillage for 22–25 cm; 3 – subsurface tillage for 10–12 cm; 4 – fallows for 40 years

CONCLUSIONS

With systematic subsurface tillage of typical chernozem there is structuring of energy reserves in the fractions of group and fractional composition, aimed at decreasing the mineralization (1.1-fold) and increasing the humification (up to 1.29-fold) and humus accumulation in the agrosystems of the

Table 5. The matrix model of interrelations between the fertility parameters of typical low-humus light-loamy chernozem.

Biogenicity CFU*/g	Humus, %	Phosphate-mobilizing micro-organisms, million/g	Mobile compounds of phosphorus, mg/100 g	Hydrolytic acidity, mg-eq./100 g	Decomposers of organic compounds of nitrogen,	Assimilators of mineral compounds of nitrogen,	Easy hydrolysable compounds of nitrogen, mg/100 g	Parameter
					million/g			
X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	
1	0.55	0.90	0.75	0.62	0.08	0.96	0.56	X_1
	1	–0.25	–0.69	–0.35	–0.85	–0.66	0.98	X_2
		1	0.67	0.79	–0.35	0.89	–0.16	X_3
			1	0.88	0.25	0.90	–0.60	X_4
				1	–0.30	0.78	–0.45	X_5
					1	0.12	–0.87	X_6
						1	–0.58	X_7
							1	X_8

*CFU – colony-forming units.

Left-Bank Forest-Steppe of Ukraine compared to ploughing.

Soil tillage does not affect the type of humus (C_{HA} to C_{FA} = 1.85−1.87), but it changes the total energy reserves C_{org} in the 0–30 cm chernozem layer. The highest values were obtained with subsurface tillage (+ 31 teracalorie/ha) compared to ploughing. As for the surface tillage, the energy enrichment is at the level of ploughing.

The systematic application of subsurface tillage on typical low-humus chernozem determines the regrouping of nitrogen forms in the nitrogen composition of peripheral chains of HA and FA towards their more available forms, which will facilitate more efficient manifestation of potential fertility along with quality change in the carbon state.

In conditions of long-term subsurface tillage both with the introduction of 6 t/ha of manure and 7 t/ha of by-products, the most efficient humus accumulation is noted for the 0–20 cm chernozem layer with simultaneous increase in its content in the lower part of the processed layer without any differentiation of accumulation. With surface tillage there is expressed differentiation in humus accumulation in the 0–20 cm soil layer (0.005 % per year), and the content of humus in the 20–40 cm soil layer decreased by 0.004 % per year. The difference between the humus content in chernozem layers is 0.45 %. When 6 t/ha of manure are replaced by 7 t/ha of by-products the intensity of humus accumulation is decreasing regardless of the way of tillage, but humus accumulation was found to be the most efficient for subsurface tillage.

The application of subsurface tillage leads to the increase in the C_{HA}:C_{FA} ratio in the 0–20 cm soil layer with subsurface tillage, which is conditioned by the increase in humification of by-products remains: the ratio increased by 110–112 %, and with surface tillage – by 105 %. Here the content of fractions of stable bioactive humus exceeded 50 %, whereas with ploughing it was less than 50 %. The relative motility index of humus demonstrates that with deep subsurface tillage there is a process of involving the fractions of labile bioactive humus into the fractions of stable bioactive humus compared to ploughing.

Soil tillage is a relevant factor of impact on the number of ecologo-trophic and taxonomic groups of microorganisms. Compared to indices of different variants of soil tillage, the biogenicity on fallows was 1.56–2.39 times less, the number of phosphorus-mobilizing microorganisms – 2–4 times less, and that of microorganisms, assimilating mineral forms of nitrogen – 2.5 times less. The application of subsurface tillage promotes the decrease in the intensity of mineralization processes, the increase in humus accumulation, better provision of mobile forms of phosphorus and mineral compounds of nitrogen for plants.

The enhanced biogenic accumulation of nutrients and local acidification of the upper third of humus horizon are useful phenomena, which should be stimulated by subsurface tillage, and not destroyed by systematic ploughing. The content of mobile forms of phosphorus in soil is directly related to the activity of phosphate-mobilizing microflora, the activity of which is maximal in the range of exchange acidity of pH_{EA} = 6.7−68. In conditions of subsurface tillage the share of ammonium form of nitrogen in the sum of NH_4 + NO_3 increases compared to ploughing. The inverse correlation was found between the intensity of nitrification and the content of available and mobile compounds of phosphorus.

Гумусовий стан чорнозему за різних способів обробітку в агроценозах лівобережного Лісостепу України

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Мета. Показати довготривалий вплив різних способів обробітку чорнозему типового малогумусного на зміну вмісту і складу гумусу та направленість процесів трансформації органічних добрив. Дослідити зміни структури енергозапасів у структурі групового та фракційного складу гумусу чорнозему типового малогумусного легкосуглинкового в агроценозах лівобережного Лісостепу України. **Методи.** Польовий, лабораторний, мікробіологічний, розрахунковий, математико-статистичний. **Результати.** Визначено, що за умов довгострокового виконання безполицевого обробітку найефективніше гумус нагромаджується у 0−20-см шарі чорнозему при одночасному збільшенні його вмісту у нижній частині оброблюваного шару без прояву диференціації у накопиченні. За поверхневого обробітку відбувається виражена диференціація у накопиченні гумусу в 0−20-см шарі ґрунту (0,005 % за рік). При заміні 6 т/га гною на 7 т/га побічної продукції інтенсивність акумуляції гумусу знижується незалежно від обробітку, але за безполицевого обробітку гумусонакопичення виявилося найефективнішим. Застосування безполицевого обробітку призводить до підвищення співвідношення $C_{ГК}$: $C_{ФК}$, що обумовлено зростанням гуміфікації рослинних решток побічної продукції у 0−20-см шарі ґрунту за безполицевого обробітку на 110−112 %, за поверхневого – на 105 %. **Висновки.** Встановлено, що за систематичного безполицевого обробітку чорноземів типових лівобережного Лісостепу України відбувається структуризація як загального запасу енергії $C_{орг}$, так і його якісного складу, спрямована на підвищення інтенсивності процесів гуміфікації та накопичення органічного вуглецю, а також зменшення мінералізації. Співвідношення запасів енергії $C_{орг}$ гумінових кислот до фульвокислот у 0−30-см шарі чорнозему незалежно від обробітку становить 1,85−1,87, що свідчить про однотипність гумусонакопичення, але загальний запас енергії $C_{орг}$ був вищим за безполицевого обробітку (+ 31 Ткал/га) відносно оранки. За поверхневого обробітку енергозбагачення було на рівні оранки.

Ключові слова: гумус, глибина гуміфікації, безполицевий обробіток, біоактивний гумус, запас енергії в гумусі.

Гумусное состояние чернозема при различных способах обработки в агроценозах левобережной Лесостепи Украины

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Цель. Показать долговременное влияние различных способов обработки чернозема типичного малогумусного на изменение содержания и состава гумуса и направленность процессов трансформации органических удобрений. Исследовать изменения состояния энергозапасов в структуре группового и фракционного состава гумуса чернозема типичного малогумусного легкосуглинкового в агроценозах левобережной Лесостепи Украины. **Методы.** Полевой, лабораторный, микробиологический, расчетный, математико-статистический. **Результаты.** Определено, что в условиях долгосрочного выполнения безотвальной обработки наиболее эффективно гумус накапливается в 0−20-см слое чернозема при одновременном увеличении его содержания в нижней части обрабатываемого слоя без проявления дифференциации в накоплении. При поверхностной обработке происходит выраженная дифференциация в накоплении гумуса в 0–20-см слое почвы (0,005 % за год). При замене 6 т/га навоза на 7 т/га побочной продукции интенсивность аккумуляции гумуса снижается независимо от обработки, но при безотвальной обработке гумусонакопление оказывается самым эффективным. Использование безотвальной обработки приводит к повышению соотношения $C_{ГК}$: $C_{ФК}$, что обусловлено ростом гумификации растительных остатков побочной продукции в 0−20-см слое почвы при безотвальной обработке на 110−112 %, при поверхностной − на 105 %. **Выводы.** Установлено, что при систематической безотвальной обработке черноземов типичных левобережной Лесостепи Украины происходит структуризация как общего запаса энергии $C_{орг}$, так и его качественного состава, направленная на повышение интенсивности процессов гумификации и накопления органического углерода, а также на снижение минерализации. Соотношение запасов энергии $C_{орг}$ гуминовых кислот к фульвокислотам в 0−30-см слое чернозема независимо от способа обработки составляет 1,85−1,87, что свидетельствует об однотипности гумусонакопления, но общий запас энергии $C_{орг}$ был выше при безотвальной обработке (+ 31 Ткал/га) относительно пахоты. При поверхностной обработке энергонасыщение было на уровне пахоты.

Ключевые слова: гумус, глубина гумификации, безотвальная обработка, биоактивный гумус, запас энергии в гумусе.

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