UDC 631.81.0.36

SOIL-REMEDIATING ACTIVITY OF AGROECOSYSTEMS AND CHERNOZEM FERTILITY RESTORATION USING LOW-CARBON TECHNOLOGIES

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Received on June 23, 2015

Aim. To present theoretical justification of the increase in potential fertility of typical chernozem with systematic application of surface tillage via the creation of soil conditions, optimal for photosynthesis, and provision of maximal physiological activity of root systems of cultivated crops to restore natural processes of soil formation in the agroecosystems of the Left-Bank Forest-Steppe of Ukraine. **Methods.** Field, laboratory, computational, mathematical and statistical. **Results.** The analysis of scientific literature and our own studies (for over 30 years) have demonstrated that the conditions of minimal tillage ensure the connection between the physiological rhythms of activity of agricultural crops, the rhythms of humus decomposition and synthesis, the fixation of carbonic acid by the heterotrophic saprophyte microflora and carbonation, restoring soil formation in agroecosystems. Agricultural crops in the agroecosystems are self-developing, auto-regulated, open systems, capable of overcoming the forces, causing the increase in entropy and forming highly regulated and dynamically stable complexes of different hierarchy. High information capacity and codification of cultivated crops defines the direction of the development of soil medium in agroecosystems. When the genetic information capacity of the development of cultivated crops resonates with the information capacity of the soil medium development, there is either the soil formation process or the process of extensive fertility restoration in agroecosystems. **Conclusions.** The maintenance and application of aboveground by-products of crop production, sufficiently compensated in terms of nitrogen using mineral fertilizers, as organic fertilizers, and wrapped up into the surface layer of chernozem during the surface tillage, simulates the natural course of nitrogen-carbon circulation in agroecosystems of different types. The restoration of the natural soil formation model in the agroecosystems is ensured by the stimulation of physiological activity of cultivated crops in the agroecosystems due to the launch of drain mechanisms of carbon with the increase in CO_2 content in the lowest atmospheric layers during the vegetation period of crops, which should be the basic model of extensive fertility restoration of typical chernozem.

Key words: soil formation, physiological activity of the root, agroecosystem, CO_2 factor, stimulating N-effect, carbonates.

DOI: 10.15407/agrisp2.02.056

INTRODUCTION

Agricultural crops in the agroecosystems are not passive consumers of environment constituents; instead they actively transform the latter depending on their needs and adjust to them at the same time. One of the manifestations of agroecosystem self-regulation is the fact that the physiological rhythms of agricultural crop activity should be balanced with the biochemical rhythms and regimes of soil stratum of chernozem, which should be deemed as the adaptation reaction to the change in conditions of external growth factors and the process of accumulating metabolic by-products for soil saprophyte heterotrophic microorganisms in the rhizosphere of cultivated crops and, as a consequence, the enhancement of natural soil formation processes in the agroecosystems [10, 11, 19, 23]. Current complicated and organically reasonable adaptation reaction of agricultural crops to the mineral nutrition in the form of humus formation is a vital physiological function of the plant organism, the basis of the process of extensive fertility restoration and soil formation of chernozem in the agroecosystem. The task, which should be demanded from the agriculture system along with the increasing performance, is to stimulate the processes of humus and soil formation in the agroecosystems [19, 20].

The biochemical reactions, resulting in the transformation of residues of exogenous vegetative material (root and after-harvest remains, root exudations) and the introduced manure into humic acids and humus, the mineralization of the latter, and, as a result, the change in the structural elements of chernozem – all these come from the activity of the living matter of the agroecosystem, the physiological activity of which determines the level of agriculture biologization [7, 8]. Soil fertility is understood as its capability of ensuring optimal regime of binding the solar energy in the soil-plant system in specific conditions. The expected result of this capability should be the accumulation of by-products for soil heterotrophic saprophyte microorganisms in the plant rhizosphere. Current complicated and organically reasonable adaptation reaction of agricultural crops to the mineral nutrition in the form of humus formation is a vital physiological function of the plant organism, the basis of the process of extensive fertility restoration and soil formation of chernozem in the agroecosystem [8–13].

It is generally believed that the direction and rate of the transformation of organic matter, coming into soil, are focused on the activity of soil microorganisms, since this part of soil biota is related to biochemical transformations of organic substances, but the direction of organic matter transformation in the annual and seasonal cycles is determined due to the result of the interaction of agricultural crops in the monoculture and the consecutive interaction of microorganisms and living organisms, their cumulative physiological activity and vital functions. The interaction of the soil microflora of the root zone, the root system and the aboveground part of agricultural plants is dominating. The character of interaction is conditioned by the system of chernozem tillage: systematic tillage disturbs the natural interaction mechanism of the following system: microorganisms of the root zone–root system–aboveground part of plants, while the systematic application of soil-protecting technologies of cultivating agricultural crops, based on the zero tillage of chernozem, stimulates and directs the development of typical chernozem towards natural ecosystems, first of all changing the soil conditions of activity of trophic constituents of the agroecosystem [23, 26, 27].

The root system of agricultural crops is the main source of physiologically active substances, which play the decisive role in the donor-acceptor interaction between plants and the microbial cenoses and plants in the soil during the whole vegetative period. Until quite recently the notion of allopathic relevance of root systems was formed in isolation from the ecologic-evolutionary and soil-formation specificities of crops in the crop rotation, which are capable of forming the soil structure via their root exudations; due to this fact the root exudation is very important for the enhancement of morphogenetic features of chernozem, the amount of which is directly related to the activity of such abiotic factors in the soil medium, as temperature, humidity, aeration, acidity, presence of nutrients [9, 18].

Modern studies demonstrate that with optimal humidity of soil the amount of root exudate is proportional to the aboveground part of the plant, *i. e.* even hoed crops of the sufficiently humid agroecosystems may be active soil-creators instead of being destructive factors for chernozem fertility as it was used to believe. The root exudate contains about 30 % of nitrogen in the organic form from its total amount in plants; 20–37 % of carbon, synthesized in plants, is spent for nitrogen-fixation processes in soil [18]. Ashy elements, absorbed by the roots during the reproductive period of development of cultivated plants, return 38–40 % K, 20–22 % Ca, 10 % Mg into the soil [6]. The root exudate [19] is one of the most active forms of natural manure. Ponomariova [20] believes that root exudates are the main source of pre-humus substances for the whole humus-fertilized bedrock of chernozem, and the root system, functioning in aerobic conditions, is physiologically active. The aerobic breathing of roots and the input of carbohydrates from the aboveground mass of plants should form the basis of cultural soil-formation. The anaerobic conditions of breathing for the roots decrease the capability of plants to consume nutrients; the protoplasm flow in the cells stops, the synthesis of proteins is disturbed, the growth productivity of agricultural crops is decreased [4, 14, 15]. The study of the mentioned issues is the basis of ecologic agriculture theory [21, 22].

The aim of the study is to present theoretical justification of the increase in potential fertility of typical chernozem with systematic application of surface tillage via the creation of soil conditions, optimal for photosynthesis, and provision of maximal physiological activity of root systems of agricultural crops via the restoration of natural processes of soil formation in the agroecosystems of the Left-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

Based on the general theory of the productive process of agricultural crops [5, 6, 17] and the main provisions of the ecologic agriculture theory [22], the attempts were made to reveal the following:

– the impact of the tillage system in the agroecosystem on the potential indices and levels of photosynthetic productivity of agricultural crops and required conditions;

– the substantiation and elaboration of the ways of targeted and reasonable increase in the photosynthetic productivity of crops in the rotation due to different systems of soil tillage.

A number of indices, most relevant from the standpoint of photosynthesis productivity assessment and the realization of these tasks, are the dynamics of root system growth; the dynamics of daily gain of dry and living biomass of plants; the level of maximal daily biomass gain in the period of the highest closing up of crops and the most intense growth of plants; the change in the structure of the aboveground biomass of plants in the generative phase of development; the biogeochemical principles and microbiological activity of the soil in agroecosystems.

The studies were conducted in the conditions of the Left-bank part of the Forest-Steppe of Ukraine in the permanent experiments of the Chair of Soil Science and Soil Protection of the National University of Life and Environmental Sciences of Ukraine (NAU) and the Cherkasy State Agricultural Experimental station of the NSC "Institute of Agriculture", NAAS of Ukraine [4, 15]. Long-term impact of the zero tillage on the restoration of typical chernozem fertility in the agroecosystems of the Left-bank part of the Forest-Steppe of Ukraine was studied in the south of Vorskla-Sula region (soil cover is presented with typical chernozem (>50 %), which was medium-humic (5.55–5.65 %), light loamy) and in the Middle Dnieper–Seym agrosoil region (typical low-humic light loamy chernozem).

Permanent experiment No. 1. The studies were conducted (1989–1996) in a multifactor permanent experiment of NAU (currently NULES) in the following chain (sugar beet–green peas–winter wheat–corn for grain–corn for silage) of 10-course grain-beet crop rotation for the southern part of the Left-bank Forest-Steppe (cereals – up to 40 %, technical crops – up to 30 %, grain legumes – up to 10 %, forage crops – up to 20 %), where four ways of tillage were investigated: tillage of different depth for 22–32 cm (deep ploughing for 22–32 cm); zero tillage of different depth for 22–32 cm (subsurface tillage for 22–32 cm); zero tillage for 10–12 cm (surface tillage for 10–12 cm); and zero tillage for 5–6 cm (surface tillage for 5–6 cm) on the background of four fertilization systems – without organic and mineral fertilizers; 15 t/ha humus + $N_{55}P_{55}K_{45}$ (low dose); 15 t/ha humus + $N_{85}P_{75}K_{65}$ (medium dose); 15 t/ha humus + $N_{110}P_{100}K_{85}$ (high dose).

Permanent experiment No. 2 (launched in 1975, still active). The registry of certificates of NAAS No. 040 "The scientific foundations of establishing crop rotations, tillage and fertilization systems in conditions of the Left-bank Forest-Steppe of Ukraine"). The studies (2003–2014) were conducted during the multifactor permanent experiment of the Cherkasy State Experimental station of NSC "Institute of Agriculture of NAAS". Two types of five-course crop rotations were investigated during the experiment: A − perennial grass–winter wheat–sugar beet–corn–barley + perennial grass (cereals – up to 60 %, technical crops – up to 20 %; perennial grass – up to 20 %); B − green peas–winter wheat–sugar beet–corn for grain–corn for grain (cereals – up to 60 %, technical crops – up to 20 %; grain legumes – up to 20 %). The fertilization system in 2001–2012: 6.0 t/ha of by-products; $N_{31}P_{33}K_{41}$ (average dose); $N_{62}P_{66}K_{82}$ (double dose). The ways of main tillage: tillage of different depth for 22–25 cm (deep ploughing for 22–32 cm) for all the crops; zero tillage for 22–25 cm (subsurface tillage for 22–32 cm) for all the crops; surface tillage for 8–12 cm for all the crops (surface tillage for 10–12 cm).

The methods of determining the indices of study objects. To register the changes in agrochemical, physical and chemical, and agrophysical indices while studying the nutrition regime, humus and agrophysical conditions, mixed samples were selected from one meter thick soil layers in 10 cm distance on different land plots following the schemes of experiments according to DSTU 7030:2009 (GSTU 46.001-96). The analysis of the samples of soil and vegetative material, the registration and calculations were conducted according to special methods: humidity − by the thermogravimetric method according to the main periods of the growth of crops (DSTU ISO 11465:2001); structure density – by the cutting ring method in Kaczynsky's modification in the periods of intensive growth of crops and yield formation (DSTU ISO 11272:2001); humidity reserves – by calculations (using the indices of humidity and structure density of specific layers of soil up till the depth of 150–180 cm); the content of general humus – according to Turin in Simakov's modification (DSTU 4289:2004); pH_{KCl} – by potentiometry (DSTU ISO 10390:2007). The content of soil air was determined by the tube method (according to Matskevich) with subsequent analysis of soil air at the gas analyzer GVV-2; the content of carbonates – by the volumetric estimation (DSTU ISO 10693-2001); the respiratory coefficient (Rc) − by calculations (according to Zboryshchuk); the intensity of CO_2 emission – by Shtatnov's method.

The lowest water field capacity (WFC) was determined by the method of flood filling; the humidity of a break in capillary links (HBC) – according to Abramova; the maximal hygroscopic moisture (MH), the withering point (WP) and the moisture of delayed growth (MDG) – by calculations according to Michurin and Litaiev. The total specific surface area was determined by the method of Kutilik; the volumetric moisture of soil – by the known density per dry mass (DSTU ISO 16586:2005). The soil biological surveys were conducted in the 0–20 cm layer of soil. The selection and storing of soil to study the aerobic microbiological processes in laboratory conditions were conducted according to DSTU ISO 10381–6–2001. The calculation of carbon balance in the agroecosystems of different types and forecast of the humus condition of chernozem as per weight of released CO_2 was performed using the following flows: Cγ – weight of carbon CO_2 after humus mineralization, t; C_p – weight of carbon CO_2 due to mineralization of by-products, after harvest and root remains, t; $C_{(\gamma+p)}$ – total weight of carbon after mineralization, t; C_j – weight of carbon CO_2 due to the breathing of soil organisms, t. The results of field surveys were statistically processed by the dispersion analysis method (Dospekhov, 1985) using Statistics-6 program.

RESULTS AND DISCUSSION

The study of the impact of different tillage systems for typical chernozem on the rate of the growth of morphological parts of plants in the starting period demonstrated that practically all the crops in the crop rotation form a considerably higher root and aboveground mass using surface tillage: while cultivating cereals in spring the growth gain of the aboveground and root mass was 2.0–2.5-fold more intense than with tillage.

While cultivating sugar beet with surface tillage the growth gain of the aboveground mass (sugar-beet top) was 1.35–1.5-fold higher, and the rate of root mass growth – 1.55–1.65-fold higher compared to the surface tillage. A similar regularity was observed while cultivating sunflower, corn for grain and silage: with zero tillage the intensity of growth of morphological parts of plants was 2.5–2.7-fold higher compared to the tillage variants.

One of the integrating factors, influencing the rate of growth of the aboveground and root mass in the starting growth period, is the structure and density of the humus bedrock, which is higher in the limits of optimal values, compared to tillage, with zero tillage in the soil layers of 0–10 and 10–20 cm, which allows forming a denser seed bed at the depth of 5–6 cm. The correlation coefficient between the structure density and the rate of growth gain (g/day) of morphological parts of plants in the starting period of growth reached the level of R = (+0.70 … −0.80) ± 0.05 for the aboveground mass and R = (+0.76 … −0.870) ± 0.04 for the root mass. The correlation between the rate of root growth and soil humidity was reverse: R = (–0.73 … −0.82) ± 0.04. The ratio of the mass of dry substance of the aboveground part and the weight of roots with tillage was 2.5–3.5 to 1, while the one with zero tillage – 1.5–2 to 1, but with higher absolute values of the ratio constituents.

The results of analysis of re-distribution of the root system of hoed crops in the humus bedrock during the critical phases of development demonstrated (Table 1) that in conditions of different systems of soil tillage the total mass increases with the minimization of tillage. There is re-distribution of the root weight in the limits of a soil layer of 0–40 cm. With the minimization of the main tillage the number of roots in the soil layer of 0–10 cm increases: while cultivating corn for silage – by 4.1–10.4 %, corn for grain – by 5.9–10.9 %; sunflower – by 10 %.

A similar regularity is remarkable for peas and winter wheat: the number of roots in the 0–10 cm layer compared to the tillage increases by 6–15 %, and the total number of roots in the 0–30 cm layer during the reproductive period of development of the mentioned crops was found to be 15–20 % higher compared to tillage.

During the crop rotation while having low depth and minimal tillage the total amount of roots in the humus bedrock was 1.12–1.2-fold higher compared to tillage, but their main amount was concentrated in the 0–10 cm layer of chernozem (40–45 t/ha) which is 82.5–87.5 %, while with systematic tillage the mass of roots was 28 t/ha, *i. e.* 64.5 % of the total mass. With deep zero tillage the indices of the content of roots and their re-distribution in the limits of humus bedrock were in-between those for ploughing and tillage surface tillage for 5–12 cm which testifies to the differentiation of the content of roots with the minimization of soil preparation (Fig. 1).

The comparison of the mass of the aboveground part of a plant against the root mass allows estimating the adaptive capabilities of agricultural crops in conditions of different tillage systems with increasing moisture deficiency. With systematic ploughing and the impact of a complex of soil and climate conditions, during the starting period of growth the plants form a root system, insignificant in size and quality indices. To compensate moisture shortage in worsening conditions of growth and a great loss of moisture due to transpiration in the period of intense increase in the vegetative mass there is considerable growth of the root system into the depth of the chernozem bulk compared to the growth of the leaf surface. This process occurs until the soil and climate conditions force the plant to re-establish the mechanism of synchronous growth of its morphological parts to the contrary one. As for soil-protecting tillage systems, due to optimization of soil conditions there is simultaneous active growth of both the root and aboveground vegetative mass. This fact conditions higher yield gain of agricultural crops using soil-protecting (low-carbon) technologies.

The structure of the aboveground mass of agricultural crops changes during the period of the initiation of reproductive organs in different tillage systems. With soil-protecting technologies on the background of average doses of mineral fertilizers ($N_{85}P_{75}K_{65}$ + 15 t/ha of humus) the total biomass of plants compared to tillage increases by 15–20 %, but it occurs due to the increase in the share of reproductive organs in the total biomass. With the introduction of high doses of mineral fertilizers ($N_{110}P_{100}K_{90}$ + 15 t/ha of humus) there is insignificant growth gain of the total aboveground biomass, the share of marketable part of which increases by an insignificant amount during the first 3–5 years of systematic surface tillage for 10–12 cm. Long-term (10–15 years) application of soil-protecting technologies stabilizes

Table 1. The impact of the tillage system of typical chernozem on the content (t/ha) and re-distribution (%) of roots while cultivating hoed crops

Soil layer capacity, cm	Corn for silage		Corn for grain		Sunflower	
	Content of roots in the 0–30 cm layer					
	tons/ha	%	tons/ha	%	tons/ha	%
Deep ploughing for 22–32 cm						
0–10	3.2	59.3	4.5	61.1	2.91	63
10–20	1.1	20.4	1.7	23.3	1.14	25
20–30	1.1	20.3	1.1	15.1	0.53	12
0–30	5.4	100	7.3	100	4.57	100
Subsurface tillage for 22–32 cm						
0–10	3.50	63.4	5.00	67.0	2.89	63
10–20	1.1	20	1.5	20.0	1.16	25
20–30	0.9	16	1.0	13.3	0.64	12
0–30	5.5	100	7.5	100	4.59	100
Surface tillage for 10–12 cm						
0–10	3.90	69.7	6.20	72	3.60	73
10–20	0.95	17	1.4	16.3	0.7	14
20–30	0.73	13.3	1.0	11.7	0.6	13
0–30	5.58	100	8.6	100	4.90	100

the share of the marketable part in the total biomass at the level of values, remarkable for average doses of fertili-zers. In conditions of systematic tillage and introduction of high and medium doses of mineral fertilizers there is active increase in the total vegetative biomass, and the share of the marketable part of the yield is lower with surface tillage for both medium and high doses of fertilizers (Table 2).

A significant factor, limiting the growth of plants and the physiological activity of the root system, is the soil temperature. In the first decade of May (Table 3) the average temperature of the half-meter chernozem layer with the surface tillage was +1.2 … –1.8 °C, and in the soil layers of 0–10 and 10–30 cm − +1.2 … –2.0 °C below the values for tillage. In June-July the temperature of the 0–50-cm chernozem layer was +0.9 … –1.6 °C, and in the 0–10-cm layer – +1.4 … –2.4 °C less.

The difference, observed in the temperature regime of chernozem with tillage during May-June, promotes 20–25 % increase in physical evaporation of the productive reserve of moisture from the depth of chernozem in the seasonal cycle. In conditions of systematic tillage the temperature of soil, increased in the summer period, accelerates the aging of the root system. It starts branching intensively with predominant thin root fractions. Here the physiological activity of root systems decreases: nutrients are almost not consumed, and the growth gain of the aboveground mass and the root exudation decrease to the critical levels. With systematic tillage during the starting phases of development (April) of field crops there is an increase in the humidity in the humus bedrock of chernozem. In these conditions there is no need for plants to have a strong root system. A high ratio between the aboveground and root mass of plant is formed.

With the increase in dryness of soil and climate conditions in May-June there is active growth of the root into the depth of the soil profile of chernozem: field crops feel the increasing deficiency of optimal moisture provision constantly. The rate of soil aridity increase is constantly surpassing that of the root mass into the depth of the profile, which results in constant increase in the ratio of the weight of the root and the weight of the aboveground weight of crops with the decrease in the absolute weight of the marketable part of the yield. The regularities determined about the growth of crops in agroecosystems are used as a basis of a false conclusion on better development of the root system in conditions of increased aridity, which is a consequence of intensive soil preparation. With minimal preparation, due to moderately developed total biomass of agricultural crops the amount of summer atmospheric precipitation, reaching the surface of the field, is higher compared to the tillage, and the depth of wetting the humus bedrock is about 15–25 cm.

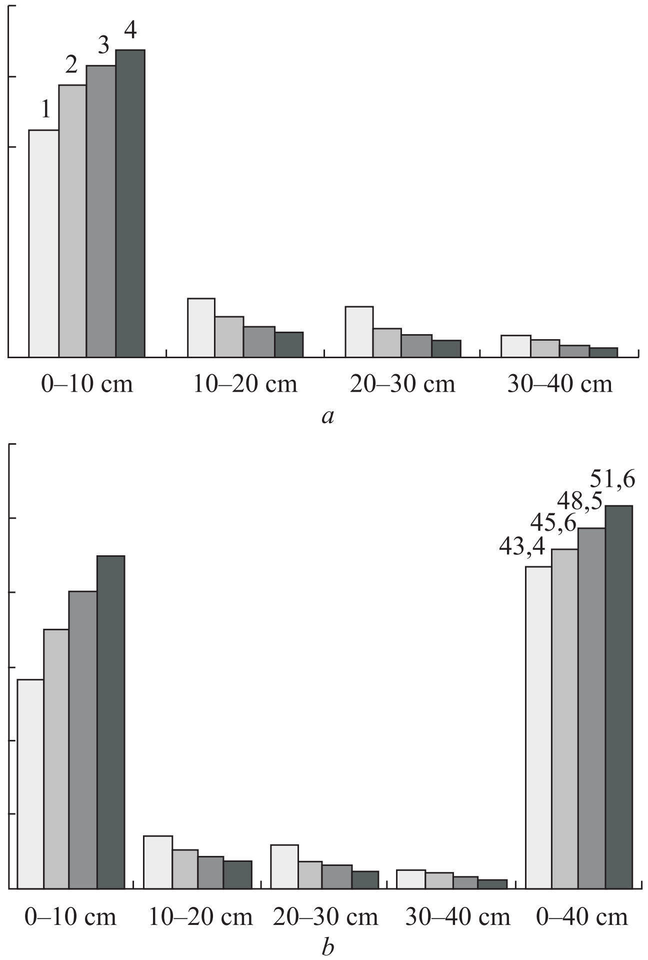

Fig. 1. The impact of the way of soil preparation on the redistribution (%) (*a*) and the storage (t/ha) (*b*) of roots in the humus bedrock of typical medium-humic light loamy chernozem in the 10-course grain-hoed crop rotation with the introduction of $N_{85}P_{75}K_{65}$ + 15 t/ha of humus: 1 – deep ploughing for 22−32 cm; 2−4 – subsurface tillage for 22−32 cm (2), surface tillage for 10−12 cm (3) and 5−6 cm (4)

High level of agrophysical condition, the presence of mulching of the soil surface and more improved agrophysical structure of the 0–30 cm soil layer are the reasons why in the driest period of the year (July–August) the soil humidity does not reach the WP values which prolongs the period of biological activity (PBA) for 20–25 days compared to the variant of systematic tillage. This fact enhances the biogenicity of soil, and the intensity of CO_2 emission by the chernozem surface increases 1.15–1.25-fold compared to the systematic tillage, which stabilizes the content of carbon acid and the turbulence of air masses during the highest density of the crops and the permanence of the cultural soil formation conditions in the agroecosystem in general (Table 4).

With intensive soil preparation of the degraded chernozem of the Left-bank Forest-Steppe there are worse quantitative indices of humidity and considerable increase in the depth of active moisture circulation which shifts to May-July and conditions deep summer drying out of the soil. The contrast of the hydrothermal regime and the accumulation of the xeromorphosis of soil conditions of the processed soils decrease the soil-restoring activity of the crops in crop rotations and increase pauses in the activity of soil mesofauna and microorganisms, which is the main reason of shortening the humus-fertilized bedrock via the enhanced mineralization processes with considerable accumulation of humus in the upper part of the soil

Table 2. The impact of the system of preparation of typical chernozem on the structure of the total biomass of agricultural crops in the crop rotation

The system of soil preparation	Total biomass tons/ha	Structure of total biomass, t/ha		The by-products/main products ratio
		Main	By-products	
Winter wheat (phase of milky-wax ripeness) N_{45} P_{65} K_{55}				
B_1	10.3	4.50	5.80	1.3/1
B_2	10.4	5.00	5.40	1.1/1
Corn for grain (phase of wax ripeness) N_{90} P_{80} K_{80} + 30 t/ha of humus				
B_1	38.4	7.90	30.5	3.8/1
B_2	41.0	9.50	31.5	3.3/1
Sunflower (phase of seed ripeness in sunflower calathium) N_{30} P_{56} K_{45}				
B_1	15.2	4.20	11.0	2.6/1
B_2	12.4	4.40	8.00	1.8/1

Note. B_1 – variant of tillage for different deep ploughing for 22–32 cm; B_2 – surface tillage for 10–12 cm.

Table 3. The impact of the soil preparation system on the temperature (°C) of the typical chernozem layer of 0–50 cm on the 8–9th year starting from the beginning of the experiment

Temperature (°C) at 12.00			
0–10 cm	10–30 cm	30–50 cm	0–50 cm
First decade of May			
+16.8/+14.8*	+13.6/+12.4	+11.6/+11.0	+14.0/+12.8
Second decade of June			
+15.8/+13.6	+14.8/+13.4	+12.6/+11.8	+14.4/+12.8
Second decade of July			
+22.4/+21.0	+20.3/+19.6	+19.3/+18.8	+20.7/+19.8
For May-July			
+18.3/+16.5	+16.2/+15.1	+14.5/+13.9	+16.4/+15.1

*Deep ploughing for 22−32 cm/surface tillage for 5−12 cm.

profile. There is steppification of the soil formation of chernozem of northern facies in the agroecosystems. Using special technological operations in soil processing, covering organic, mineral fertilizers, after harvest remains and by-products from the previous crop at the depth of 10–12 cm and simultaneous mulching of the field surface with non-marketable part of the yield, the farmers have to activate the activity of soil biodiversity and the root systems of agroecosystem crops, eliminating the abovementioned consequences of the systematic tillage.

Deep intensive tillage increases the surface with the processes, related to the exchange of substances and energy in the soil. With considerable tillage there is soil inoculation of the lower part of the arable land by the upper part of the humus bedrock, due to which there is an outbreak of biological activity in the processed soil layer, but two months later the humus bedrock of chernozem is differentiated by the cellulosolytic activity, and one year after the intensive mixing of the soil the availability of nutrients in the lower part of the humus bedrock decreases by 55–65 % by the content of mineral nitrogen, by 30–36 % – by the content of phosphorus, and by 20–25 % – by the content of potassium.

On the other hand, it was established that after intensive processing the restoration of natural differentiation of different layers of humus bedrock by fertility requires 2–2.5 months even in conditions of preserving summer fallow. The renewal of natural differentiation of soil by fertility starts since the moment of revolving hunks in October–November, and in May-June of the next year the starting stage of natural differentiation of the arable layer by fertility is renewed: the upper third of the humus bedrock has a higher index of biological activity, which is several orders lower than that for zero tillage. During this period the root system grows deeper into the soil profile, impoverishing the 0–15 cm soil layer with active (physiologically active) roots, which disturbs the chemotaxis level between the root system and the soil microflora. The systematic ploughing “separates” the active pool of soil microorganisms and the root system to different sides of the arable layer. There is increased mineralization of humus in the surface layers of chernozem and the decrease of biological activity in the lower part of the arable layer with the main mass of roots. In these conditions the intensity of nutrition processes and biological activity of the soil deteriorates, which requires the introduction of higher

Table 4. The impact of the soil preparation system of typical chernozem on the interval value of field humidity (%) in July-August for 10 years of surveys

Soil layer capacity, cm	Deep ploughing for 22–32 cm	Tillage for	
		subsurface tillage for 22–32 cm	surface tillage for 5–12 cm
0–15	17–12	17–20	19–25
15–30	18–13	16–21	18–26
0–30	17–14	17–21	18–25
Category of soil moisture	MDG-WP-MH	HBC-MDG	WFC-HBC-MDG

Note. MDG – moisture of delayed growth; WP – withering point; MH – maximal hygroscopic moisture; HBC – humidity of a break in capillary links; WFC – water field capacity.

Table 5. The impact of the soil preparation system of typical chernozem on qualitative properties of the root system of winter wheat in the tillering stage

The system of soil preparation	Specific adsorption surface of the root system, m^2/g		
	Total	Active	Not active
Deep ploughing for 22–32 cm	2.97	1.42/49.0*	1.47
Subsurface tillage for 22–32 cm	7.70	3.20/42.0	4.50
Surface tillage for 10–12 cm	6.80	3.50/52.0	3.30

*(m^2/g)/%.

norms and doses of fertilizers. The natural organization of biochemical processes in chernozem is disturbed.

With the systematic surface tillage the processes of exudation and saturation of the soil depth with root exudate are more intense compared to those with tillage. The test-probes demonstrated that the rate of growing the roots of indicative plants of garden cress in the vegetative period with zero tillage was 5–10 % higher, and in some years – 20–30 % lower compared to the variant of systematic tillage which is an indirect indicator of higher root exudation [23, 25]. The study of the biological activity of the soil revealed that the systematic zero tillage with the introduction of a sufficient amount of mineral and organic fertilizers does not decrease the intensity of the activity of cellulose-destroying microorganisms, and in these conditions the root exudates become a stable source of nutrition of plants and soil microorganisms on condition of maintaining scientifically grounded crop rotation. The intensity of cellulose decay was 1.3-fold higher compared to tillage.

The system of soil preparation in the crop rotation has a considerable impact on qualitative features of the root system (Table 5). The overall adsorption surface of the root system with minimal treatment of cereals is 2.3–2.6 times higher in size compared to tillage. With zero tillage the active part of the adsorption surface of the root system is 44–52 % from the total surface, and its absolute value was found to be 2.4–2.6 times higher compared to tillage, which results in the increase in the content of nitrogen and some ash elements in the roots and aboveground biomass of agricultural crops. The surveys of Shykula and Makarchik [25] demonstrated that with zero tillage the content of nitrogen in the roots is 1.20–1.25 times higher, K_2O – 1.35–1.45 times higher, phosphorus – 1.07–1.22 times higher compared to tillage, and the biological circulation of nitrogen and ash elements accelerates 2.4–4.4 times compared to tillage. With soil-protecting technologies the change in the qualitative indices of the root systems promotes the enhancement of the root exudation.

A relevant property of the soil microflora is the capability of chemotaxis. Due to biological active substances, coming into the soil with root exudations, there is programming of the impact of cultivated plants on the development and activity of trophic groups of microorganisms, participating in and directing the transformation of the organic matter in the soil. The volume of root exudates of agricultural crops is 10–25 % of the photosynthetic production of plants which is in proportion to the amount of the aboveground mass of agricultural crops [18]. The dominating components of the root exudates are sugars, amino- and organic acids. The root exudate of legumes contains cystine, cysteine, aspartic acid, serine, glutamin, glutamic acid, threonine, alanine, tyrosine, valine, phenyl alanine, leucine, isoleucine, and the root exudate of corn – cystine, cysteine, ornithine, lysine, serine, glycine, glutamin, threonine, glutamic acid, alanine, proline, valine, phenyl alanine, leucine, isoleucine. The study of the spatial distribution of root exudates demonstrated that the root exudates in observable amounts are located at the distance of 2.5–3.0 mm from the surface of the root, *i. e.* in the rhizosphere zone. The following substances of carbon nature were revealed in the root exudate: oligosaccharides, mono- and di-sugars, glucuronic and galacturonic acid. The vegetable sugars are exudated by young plants with the root exudate and quickly consumed by the soil microflora [5, 6].

The root exudates in the root rhizosphere are potential chemoeffectors for microorganisms, as their concentration gradient in the soil determines the chemotaxis of trophic groups of microorganisms regarding one or another substance on the pre-contact level. At the same time there is recognition of potential symbionts in the form of exchanging specific signaling molecules, present in the root exudate and the aboveground part of the plant. These molecules may be nucleic acids, lectins, enzymes, substances of flavone and carbon nature. The exchange of specific signals between the plant and groups of microorganisms results in biochemical, morphological and physiological changes in the reverse reaction of each symbiont and the subordination of different trophic groups of microorganisms to the state of functioning as a unified organism. Considering the relevance of chemotaxis in the recognition of soil microorganisms of “their own” plants by the trophic groups, taxis reactions are divided as follows: taxis to simple molecules (sugars, organic acids, aminoacids), the result of which is non-specific involvement of a wide range of microorganisms into the root rhizosphere, and taxis to large molecules, distinguished by plant tissues (flavones, hormones, lectins, enzymes) in the framework of the very rhizosphere, which determines the exchange of specific signals between the plant and soil microflora [17].

The root exudation is maximally manifested when the content of humus in soil in the seasonal cycle reaches the minimal value and there is a process of heterotrophic fixation of CO_2 by soil microflora. There is the accumulation of carbon from the soil air and soil (CO_2 in the soil solution) by heterotrophic microbes with their formation of a new organic matter with 30–42 % of protein and 1–5 % lipids. These organic substances are in protoplasma, and with autolysis of microbes (breakdown of the envelope) they enter the soil solution and interact with soil intaking complex, restoring the nitrogen-containing radicals of humic acids. At first they enter the fulvates, then (with their condensation) they supply stable humates, which is accompanied with the increase in ATP content in the soil by 25–250 %. With minimal tillage it should be related to the activity of heterotrophic saprophyte microorganisms.

The root exudates contain aminoacids, amines, amides and prohumus fragments, which may be involved in the restoration of organic matter in the soil by the complementarity principle. Certainly, not the whole volume of the root exudate is transmitted to the humus content in the soil.

In June its considerable part is populated by saprophyte heterotrophic microflora, for which this substrate is physiologically more active. The mentioned process is a biochemical mechanism of restoring humus and self-regulating soil fertility of chernozem in the agroecosystems.

Due to the launch of the biochemical mechanism of humus restoration on condition of applying zero tillage there is renewal of seasonal pulsation of humus, which is determined by the seasonal physiological activity of crops in the agroecosystem, the activity of heterotrophic microflora, and which masters the set of physical, physical and chemical, agrochemical, and biochemical indices. The wider the amplitude of the seasonal change in the humus content with zero tillage is, the closer the connection is between the genetic rhythmics of the development of agricultural crops and the restoration of informative (coding) principles of soil formation for chernozem in the agroecosystems (Fig. 2).

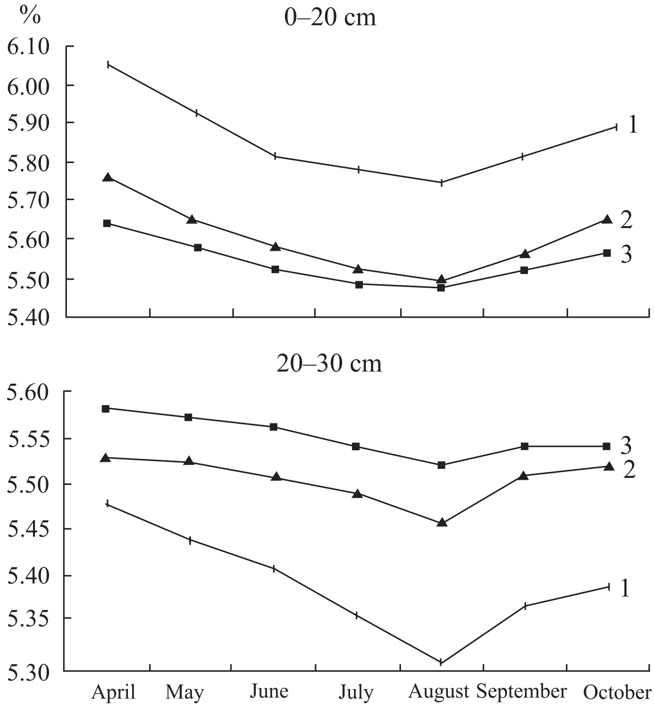

Fig. 2. The impact of different ways of tillage and maintenance (1 – fallow, 10–15 years; 2 – surface tillage for 10–12 cm; 3 – deep ploughing for 22–32 cm) of typical medium-humic light loamy chernozem on the seasonal dynamics of humus with the introduction of $N_{85}P_{75}K_{65}$ + 15 t/ha in the typical grain-hoed crop rotation of the Left-bank Forest-Steppe of Ukraine [24, 27]

Table 6. The impact of the soil-protecting technologies on the humus state of typical chernozem on the 10th year from the beginning of the surveys with the introduction of $N_{85}P_{75}K_{65}$ + 15 t/ha of manure during a crop rotation

Soil layer capacity, cm	Total humus		Humus substances and capability of peptization (1 + 2 fractions of HA) according to Hodlin		
	%	tons/ha	%	tons/ha	Motility, %
0–30	5.61/5.66*	195/215	2.08/2.23	79.0/82.0	53.0/42.0
30–40	4.58/4.73	247/275	1.95/1.81	69.0/63.0	50.0/40.0
40–70	3.49/3.75	117/125	1.50/1.38	48.0/38.0	49.0/38.0
70–100	2.29/2.53	78.0/87.0	1.10/1.15	38.0/29.0	69.0/35.0
$HCP_{0.95}$					
0–40	0.05	10.5	0.11	5.0	5.0
40–100	0.12	12.0	0.23	12.0	9.0

A – subsurface tillage for 22−32 cm; B – surface tillage for 10−12 cm.

The systematic application of zero tillage in the crop rotation stimulates the manifestation of the abovementioned mechanism via more optimal wetting and increased biogenicity of the soil conditions, which allows ensuring the water-soluble state of pro-humus and humus substances at the moment of their formation and leads to deep saturation of the depth of chernozem with the solution of humic acids, pro-humus substances and $Ca(HCO_3)_2$ [19, 20]. Due to this fact there is intensive deep saturation with pro-humus substances (for the depth of regular wetting of the soil profile), mainly with humates Ca of the second fraction (HA-2) of humic acids. The formation of humates Ca occurs both in natural conditions of soil formation and in the agroecosystems, but in the latter case it is even more intense due to permanence of hydrothermicity in the seasonal cycle (Table 6).

The increase in facial humus accumulation in conditions of minimal soil preparation occurs due to the provision of HA-2 with high migration ability at the moment of their new formation in conditions of increased hydromorphism of the soil stratum of chernozem in the seasonal and annual cycles. The optimal agrophysical structure of the humus-fertilized bedrock maintains the concentration of carbon acid in the soil air at the depressive level (>1.20–1.22 %) for reduction-oxidation processes, which ensures deep humification of newly formed humus substances and root exudate: their optical density increases by 10–15 % [25].

Humic acids are connected to Ca, have high optical density, are capable of penetrating through the stratum of carbonate eluvium into the soil-forming material [19, 20]. With systematic tillage in conditions of deep aridization of the chernozem stratum during the summer period the newly formed humus substances dry fast, which accelerates their mineralization and decreases the migration ability by the chernozem profile. In the first case there is “northerning” of the soil-formation of southern facies chernozem, and in the second – the process of steppification of the soil formation of northern facies chernozem in the agroecosystems.

The microflora of root rhizosphere changes during the vegetative period and mainly bacteria and microscopic fungi reproduce in the zone of young roots, while at this time the roots extract sweeteners, which are consumed fast. When the root system reaches maximal size, the population of heterotrophic saprophyte microorganisms grows on the surface of the root and in the rhizosphere. During tillage it grows into the soil depth, and with minimal soil preparation – by the “turf cover” type, *i. e.* on the surface. When the phenomenon of chemotaxis, stimulating the formation of stable trophic groups of saprophyte heterotrophic microorganisms, is taken into consideration, the surface location of the root system looks more natural. Therefore, the main mediator of the differentiation of the humus bedrock of chernozem by the biological activity is the location of the root system by the “turf cover” type, when the chemotaxis phenomenon has its maximal manifestation and ecologic reasonability and should be viewed as informative coding of the soil formation in the agroecosystem. With the stimulation of the root system growth into the depth of the humus bedrock of chernozem the chemotaxis is manifested less, and the decrease in the number of roots in the 0–10 cm layer disturbs trophic interactions in the rhizosphere-root system which does not promote the restoration of chernozem fertility in the agroecosystem.

Stable groups of soil microorganism associations are formed in natural ecosystems, remarkable for some fluctuations in their number and the presence of strong correlative relations between the microorganisms of zymogenic, autochtonous, eutrophic and oligotrophic blocks. The systematic minimal tillage in the agroecosystem on the background of optimal introduction of organic and mineral fertilizers promotes the formation of stable trophic groups of microorganisms with clearly defined spatial reference to the 0–15 cm soil layer and provides for the restoration of their ecologically reasonable seasonal dynamics and improvement of humus state of chernozem. The location of root systems of cultivated plants in the upper part of the humus bedrock of chernozem is decisive in this process [3, 4, 19].

With the systematic minimal tillage the intensity of soil breathing (mg of CO_2 per 100 g of soil) in the 0–15 cm soil layer was 1.10–1.15 times higher, and with the introduction of organic and mineral fertilizers – 1.15–1.25 times higher compared to the systematic tillage. Here the content of carbon acid in the soil air was more stable: 0.65–1.05 % (0–10 cm), 0.78–1.29 % (10–30 cm) against 0.29−1.05 % and 0.60−1.55 % with tillage. With minimal tillage the threshold concentration of CO_2 for depressive phenomena in the reduction-oxidation processes (1.21–1.25 %), when the humus oxidation is restrained, was more stable in time compared to ploughing [11].

The main agent of oxidative reactions of breathing in soil, determining the formation and dynamics of CO_2 in soil air, is the activity of the roots [4, 18]. The biochemical essence of soil formation is the interaction of root systems of plants with the soil and external medium, where high, physiologically unreasonable use of photosynthesis products for the breathing of roots is of utmost relevance. In the soil stratum the descending flow of carbohydrates, transforming into CO_2 in the breathing process, meets the ascending flow of moisture from the roots into leaves. With the breathing of the roots the energy-deprived carbon acid is subject to hydrolysis and transforms into the active acid form in the soil solution. The soil carbon acid, formed by the living matter of the agroecosystem (the roots of plants and microorganisms) behaves differently from the one, introduced artificially or extracted during the oxidation of the organic matter of the soil [16, 28].

Under the impact of CO_2 the soil moisture and the moisture of atmospheric precipitation are transformed into the active form due to the formation of hydrocarbonates and then – simple carbonates. The carbonation in chernozem is assumed to be related to CO_2, formed by the living matter of the agroecosystem. The carbon acid, released during the "carbon acid" breathing of the soil stratum due to degasation of carbonate-clay, carbonate deposits of loessial layers and during the oxidation of the organic matter of soil, does not participate in the formation of carbonates, but is consumed by plants in the photosynthesis process [28].

With surface tillage for 10-12 cm due to the increase in the degree of hydromorphic feature of chernozem stratum (due to the convectional-diffuse transfer of moisture along soil profile) the main mass of the roots is concentrated in the chernozem stratum of 0–170 cm, where the conditions are established for high physiological activity of the root systems of agroecosystem crops. The increased degree of hydromorphic feature of typical chernozem in the agroecosystems with zero tillage is required to create the conditions of enhancing the soil-restoration activity of the root systems with subsequent deep saturation of the chernozem stratum with root exudate and the provision of the water-soluble condition of the pre-humus and humus substances at the moment of their new formation [19, 20, 27]. These facts bring the evidence that systematic application of zero tillage in agroecosystems directs the dynamics of soil-formation of chernozem towards the enhancement of the biologization of processes, and the indicators of this phenomenon are the process of secondary carbonation, the change in the form of carbonates and the enhancement of morphogenetic features which are required to keep chernozem in the state of a fallow and wild land [23].

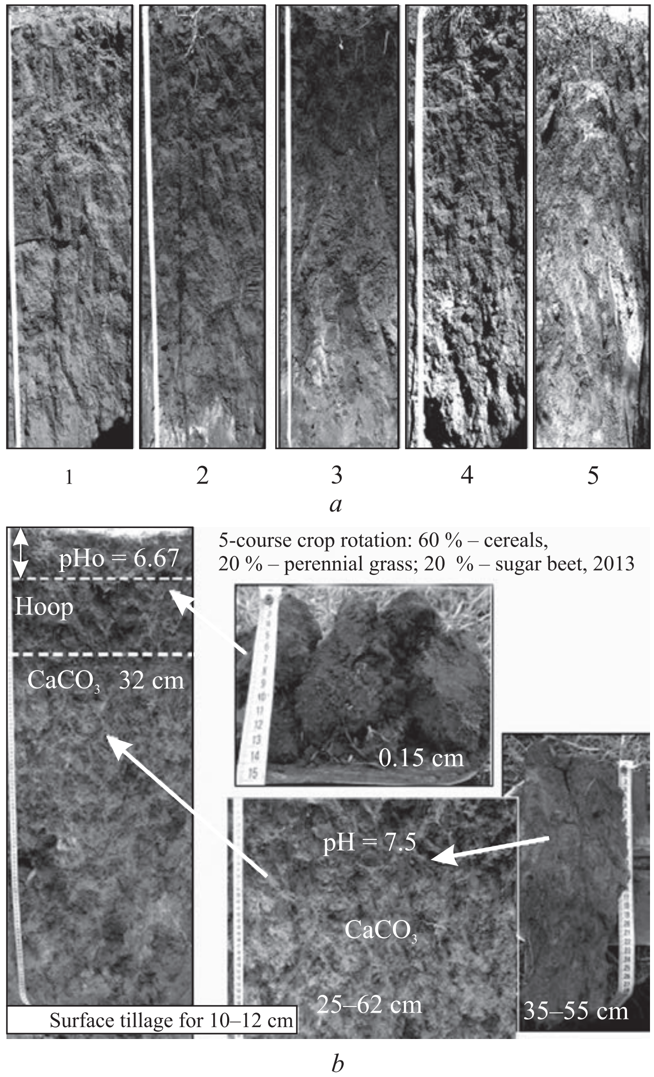

Fig. 3. Long-term (35 years) impact of the way of soil preparation on the restoration of morphogenetic features towards natural processes of soil-formation (*a*) and the manifestation of secondary carbonation features (*b*) of typical low-humus light-loamy chernozem of the Left-bank Forest-Steppe of Ukraine: 1 – deep ploughing for 22–32 cm; 2 – subsurface tillage for 22–32 cm; 3 – surface tillage for 10–12 cm; 4 – grass; 5 – fallow, 35 years

The phenomenon of enhancing the remaining morphogenetic features of natural soil formation with the systematic application of soil-protection technologies was revealed by us: the undulating horizontal split, separating the humus bedrock into H_{til} and $H_{p\backslash til}$, vanished along with the features of a "plow sole" in the 30–42 cm of soil, and the lower part of the humus bedrock acquired grain-lumpy structure and bulkiness with well-manifested aggregate and inter-aggregate porosity; the roots grew by the "turf" type and the whole humus bedrock was well-saturated with it, there were

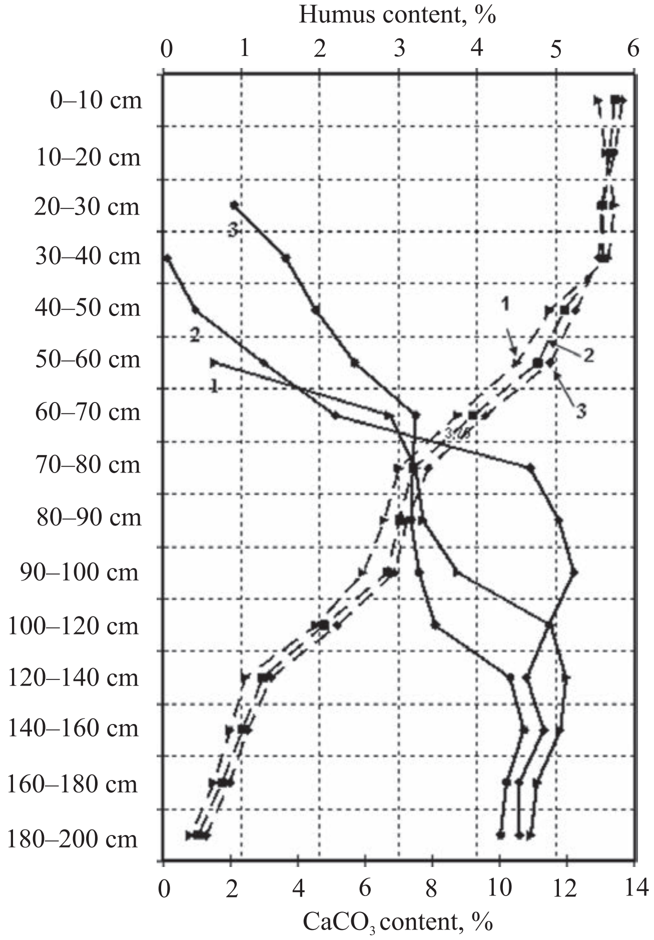

Fig. 4. The profile distribution of the content of humus (%) and carbonates (%) for different ways of soil preparation for typical medium-humic light loamy chernozem in 10-course grain-hoed crop rotation at the end of the latter: 1 – deep ploughing for 22–32 cm; 2 – subsurface tillage for 22–32 cm; 3 – surface tillage for 10−12 cm)

many worm channels with a high number of coprolites (Fig. 3).

The whole humus bedrock (H + $Hp_к$) acquired homogeneous structure with the increase in the structure formation in the 0–50 cm soil stratum. The small roots have a great number of low-grain water-resistant aggregates similar to the fallow, which is the evidence of high physiological activity of the root systems of agricultural crops and microorganisms.

With secondary carbonation of typical chernozem in the agroecosystems there is renewal in soil-formation; the hydrothermal conditions of transforming stable forms of soil carbonates into mobile ones are modeled due to which the stratum of typical chernozem is saturated with their new forms under the impact of systematic zero tillage of soil, including the covering of organic and mineral fertilizers at the depth of 10–12 cm and mulching of the field surface with after harvest remains and non-marketable part of the yield.

The soil formation in the agroecosystems of the Left-bank Forest Steppe of Ukraine is conditioned by optimal moisture saturation and stability of chernozem in thermodynamic state which determines the maximal amplitude of the half-period of relaxation of autofluctuating and cyclic processes in the soil–plant–atmosphere system. This condition of chernozem is ensured when the moisture in the chernozem stratum does not drop to the values of WP and is mostly manifested in the following interval: MDG (moisture of delayed growth) – HBC and 75 % lowest WFC (Table 7).

Surface tillage of the soil, including the mulching of the field surface with after-harvest and postcut remains promotes the increase in the hydromorphicity of the chernozem stratum during the driest season, which ensures PBA prolongation for 25–30 days compared both to natural facial values and PBA in the typical chernozem, which is in the state of enhanced xeromorphosis due to intensive preparation (ploughing) in similar facial conditions. It allows restoring the soil formation in the agroecosystems, manifested by the “rejuvenation” of carbonates in the soil profile of typical chernozem of the Left-bank Forest-Steppe of Ukraine (Fig. 4). There is regradation of degraded typical chernozem (coming

Table 7. The impact of the soil preparation system on the content (mm) and saturation (%) of typical chernozem of the Left-bank Forest-Steppe with soil moisture in July

Soil layer capacity, cm	Deep ploughing for 22–32 cm	Tillage for	
		subsurface tillage for 22–32 cm	surface tillage for 10–12 cm
0–100	(50−130)/(25−70)*	(56−140)/(34−78)	(65–150)/(36–85)
100–200	(80–130)/(40–70)	(95–145)/(55–85)	(110–150)/(65–88)

*(Reserves of productive moisture, mm)/(Moisture saturation in the range of available moisture, %).

back to earlier stages of soil formation) in the agroecosystems of the Left-bank Forest-Steppe of Ukraine.

The solubility of carbonates in chernozem is determined by the partial pressure of CO_2 of the soil air, qualitative composition of the soil solution, activity of Ca^{2+} ions and the reaction of the soil medium (pH). High activity of calcium in the soil solution with surface tillage testifies to the fact that calcium has a great resource of energy, required for the transition from the exchangeable state into the soil solution during the migration by the soil profile. The abovementioned process is conditioned by depressive concentration of carbon acid of the soil air and the moisture optimum in the seasonal cycles in case of systematic surface tillage.

With zero tillage the calciferous potential (pCa) of chernozem has the values pCa = 6.32–5.56 compared to pCa = 5.85– 5.95 for ploughing which ensures the formation of soluble forms of carbonates due to greater resource of energy for the transition from the exchangeable state into the soil solution. There is re-crystallization of granular calc-spar into microgranular calc-spar and calc-spar-lublinite.

The capacity of the zone of activated carbonates in the chernozem profile with zero tillage increases 2–6 times compared to systematic ploughing. There are natural mechanisms, regulating the limits of carbonate solubility and their release beyond the profile of their localization: CO_2 content in the soil air (from 1.0 to 1.22 %) correlates directly with $CaCO_3$ solubility, and when reaching the depressive concentration of carbon acid in the soil air the solubility of carbonates slows down and starts decreasing gradually. The depth of carbonate location and the character of new carbonate formations in chernozem reflect the specificities of hydrothermal regime during different ways of chernozem preparation (Fig. 4).

Rather shallow autumn-spring wetting and fast drying-out of the humus profile in spring and summer in conditions of intensive preparation promote the formation of “dead” bedrock and result in shortening the period of ascending flows of moisture, preventing the formation of the migrational forms of carbonates and causing their segregation into floury forms with different cementation level, which are localized in the humus profile in the form of carbonate eluvium. With the building-up of the degradation processes the carbonate eluvium is cemented in the transitional bedrocks of chernozem.

To wash the dissolved mass of $CaCO_3$ beyond the lower limit of the humus bedrock, it is required to create the washing regime of wetting the chernozem stratum during the warm period of the year [1, 2], but in the conditions of the Left-bank Forest-Steppe the amount of atmospheric precipitation for the vegetative period wets the chernozem stratum for 50–75 cm in the years with excessive moisture and for 25–45 cm – in the years with optimal and dry conditions. Even with excessive amount of precipitations in autumn with surface tillage the dissolved forms of carbonates are washed out not deeper than during the annual spring wetting of the chernozem stratum. With different systems of chernozem preparation in spring the capillary moisture moves towards the evaporation surface with simultaneous transfer of soluble forms of carbonates and their crystallization. Depending on the intensity of evaporation (the rate of HBC values increase) the crystallization of carbonates in the form of pseudomycelium occurs at different depth levels from the evaporation surface: with tillage – in the lower part of the humus bedrock, and with minimal surface tillage – in its upper part.

The farmers faced the phenomenon of secondary carbonation of chernozem in the Left-bank Forest-Steppe in historical dimension while applying the fallow system of agriculture, when shallow soil preparation with a plough and wooden plough promoted dragging carbonates towards the surface of the soil profile. It decreased the realization of potential fertility via its active form due to carbonate “salination”, the negative impact of which was eliminated by transferring the land into the fallow state, and in our studies – by grassland renovation using perennial cereals, which decreased the level of $CaCO_3$ coagulation to natural values, similar to those of a fallow, on the 8–10th year. One of the reasons of elaborating the soil preparation of different depth was the attempt to overcome the consequences of secondary carbonation to enhance the realization of the efficient fertility restoration in the existing agroecosystems, since shallow soil preparation with a plough or wooden plough and less intensive varieties were not capable of a sharp decrease in the level of natural and potential fertility of chernozem in a short period of time. The soil preparation for different depth levels allowed controlling the process of carbonate “salination” and solving a number of relevant issues of manifesting efficient fertility as well as not withdrawing the land, used as fallows.

With systematic deep tillage of the typical chernozem of the Left-bank Forest-Steppe of Ukraine, when the moisture circulation is activated in the spring-summer period, the manifestation of migration-pulsation regime of carbonates by the sporadic type requires slow increase in positive temperature after transition over 0 °C in spring and a prolonged spring period (up to 65–70 days). In these conditions the capillary-suspended moisture acquires the properties of movement continuity towards the evaporation surface in the limits of the wetted stratum of carbonate bedrock, which provides for the dragging of soluble carbonates to the humus bedrock. With the intensification of climate dryness during recent 10 years the spring period is reduced to 30–35 days with active increase in the sum of active temperatures, which, being in May, correspond to those of the summer period; it causes rapid warming-up of the soil stratum of chernozem, intensive moisture evaporation from it and the break of moisture in the soil capillaries. Due to the above-mentioned reasons the migration-pulsation regime of carbonates by the sporadic type is impossible or considerably limited in annual repeatability with systematic tillage.

With the latter, especially with the reduction of its depth, there is enhancement of hydrogenous-accumulative process of chernozem carbonation as a process of secondary accumulation of $CaCO_3$ in the humus bedrock of typical chernozem due to the increase in the hydromorphism degree and biogenicity of the soil conditions in the driest period. On the one hand, there is the dissolution of stable forms of carbonates with eluvium accumulation, and on the other – the enrichment with new forms due to the increase in the physiological activity of the root systems of crops in the agroecosystems during the critical phases of vegetation and for the re-utilization from the by-products during the after-harvest period. This is confirmed by the presence of a great number of encrusted forms (tarnish, bloom, pseudomycelium, patches, streaks) and $CaCO_3$ emissions on the inner surfaces of the soil stratum of typical chernozem.

With surface tillage typical chernozem acquires the specificities, remarkable for mycelial-calcreous chernozem due to the increase in the biogenicity of soil conditions and the accumulation of carbonates *in situ*, as well as the restoration of their seasonal migration by the soil profile. In spring there is annual presence of carbonates in the humus bedrock which gradually brings chernozem closer to surface-coagulated soil. It should be deemed as the process of regradation of degraded typical chernozem, which is a determining feature of the soil formation in the agroecosystems of the Left-bank Forest-Steppe of Ukraine.

There is observed close correlation between the content of carbonates, the structure density and the humus content in the chernozem stratum of the Forest-Steppe and Steppe zone: a direct correlative connection (R = (+0.58 … –0.67) ± 0.05) between the structure density of the stratum, accumulating stable forms of carbonates, (HPc and Ph_r) and the content (%) of carbonates; a reverse relation (R = (–0.58 … –0.69) ± 0.04) between the content of humus (%) and the content of carbonates, and the connection between the humus content (%) and the structure density was found on the level of strong reverse correlation (R = (–0.65 … –0.70) ± 0.04). The activation of carbonate eluvium in the chernozem stratum with soil-protecting soil preparation promotes the mellowing of the soil stratum of the accumulation of stable forms of carbonates: the structure and water resistance capacity of the soil structure of genetic bedrock are improved, and, as a result, the structure density decreases and the water permeability of deeper bedrocks of the soil profile of chernozem improves.

The enhancement of soil hydromorphism in the chernozem stratum does not change to the level, remarkable for leached chernozem, the physical and chemical conditions of chernozem restoration correspond to the indices of modern soil formation with fallows, and the curves of profile re-distribution of humus and carbonates do not have any leakage character, which testifies to the absence of leaching processes. With soil-protecting technologies the chernozem in the Forest-Steppe acquire some properties of mycelial-calcreous chernozem due to the enhancement of hydromorphism, biogenicity of soil conditions and the tendency to accumulate carbonates *in situ*. In spring there is the migration of carbonates into the humus bedrock which gradually brings chernozem closer to surface-coagulated soil. There is regradation of degraded chernozem or, more precisely, the natural process of soil-formation for chernozem in the agroecosystems is enhanced. With the increase in the hydromorphism of the soil conditions due to systematic minimal tillage the carbonates are drawn to the humus bedrock instead of being washed out beyond its boundaries, like it happens during leaching processes, which is regulated by the depth of annual wetting of the soil stratum in spring and enhanced humification of the organic matter.

The condition, required for the yield increase of cultivated crops, is the intensification of growth processes on the background of a reduction in the average indices of photosynthesis. The latter tendency, observed in the fields, is conditioned by the fact that the main optimizing factors of crop performance in the agroecosystems, such as moisture regime, mineral nutrition (especially improved nitrogen nutrition) and the ways of their change (intensive soil preparation) are the strongest activators of growth processes during the build-up of the total biomass of plants in the vegetative phase of development, conditioning the “mesophitisation” phenomenon in plants, which is related to the loss of xeromorphosis features by the leaves of plants. The leaves increase in their size, but become thin, forming leaf tissues with large cells and a smaller number of breathing cells per a surface unit with smaller venation pattern and photosynthesis intensity [5, 6].

The optimal photosynthetic apparatus is formed during 1.5–2 months from the emergence of seedlings of cultivated crops. It should provide both the biomass growth and yield formation, and its own intensity level with organic substances and energy. In addition to the abovementioned, photosynthesis should condition balanced growth of plants in general and compensate the input of materials and energy for breathing. In different conditions there is a deviation from the norm both towards the deterioration of soil and climate indices of photosynthetic activity manifestation and towards their excessive improvement. In the latter case the excessively developed leaf mass is capable of providing neither for its own needs nor for the needs of the whole plant organism, which leads to its premature aging and dying. Here the content of free metabolites decreases, due to which there is a lesser share of reproductive and storing organs in the total biomass of cultivated crops of the agroecosystem [8].

The ratio of indices of values and quality of the yield is in contradiction on the background of high provisions. This phenomenon is observed in conditions of systematic ploughing of chernozem of the Forest-Steppe of Ukraine. The systematic application of soil-protecting technologies in the agroecosystem corrects the abovementioned imbalance in the development of plants. The cultivated crops have a vital property which allows them to play the role of a biogeochemical factor in the agroecosystem. This is the capability to form a complicated producing photosynthetic system, adjusted to more complete use of the flows of energy and nutrition substrates on large fields of agrolandscapes. In conditions of soil-protecting agriculture, based on surface tillage, this determining role of cultivated crops increases – they become active soil-organizers in the agroecosystems.

Using by-products as organic fertilizers and zero tillage, carbon circulation in the agroecosystems of crop rotations strives to acquire natural organization that leads to the increase in the reserves of terrestrial carbon which is conditioned by increased CO_2 emission from the mineralization of by-product excess into the atmosphere. In its turn, it triggers performance enhancement of agroecosystems due to increased accumulation of CO_2 by the agroecosystem crops. In these conditions the impact of a CO_2-factor is increased in the agroecosystems of crop rotations, which acquire the properties of drainage systems [30].

Table 8. The impact of the way of soil preparation, the kind of organic fertilizers on the intensity of the balance of nitrogen and carbon in the agroecosystems of five-course crop rotations in the Left-bank Forest-Steppe of Ukraine

Index	Balance intensity, %		C_{org} in soil	C_{org} (CO_2)
	N	C_{org}		
	in agroecosystems			
The way of soil preparation				
Deep ploughing for 22–32 cm	94/100*	84/95	80/105	50/125
Subsurface tillage for 22–32 cm	99/103	86/88	89/115	45/115
Crop rotation				
with green peas	67/110	60/62	60/115	30/111
with perennial grass	97/130	57/65	100/115	50/95

*(6 t/ha of humus)/(7 t/ha of by-products).

The activity of the root systems of cultivated crops is triggered due to the optimization of nitrogen-carbon circulation in the agroecosystems of different types, causing the increase in the reserves of terrestrial carbon with the intensification of a heat resource, caused by enhanced CO_2 emission from the mineralization of the by-product excess into the lowest atmospheric layer by the density of crops and the release of mineral forms of nitrogen into the soil, which increases the performance of agroecosystems due to the "stimulating N-effect" and atmospheric CO_2 pick-up. In these conditions enhanced enrichment of the aboveground layer of crop density with carbon acid promotes the accumulation of organic carbon in agroecosystems *i. e*. the higher dependence of the performance of agroecosystems is on the intensity of nitrogen assimilation which entered the system of the agroecosystem, the faster the emission of CO_2 due to the mineralization is consumed [30–38]. According to the data of Stasik *et al*., the 1.4–1.45-fold increase in CO_2 concentration in the lowest atmospheric layer leads to the increase in photosynthesis intensity by 23–25 %, and the efficiency of using the solar radiation increases 1.2–1.22 times, which ensures the increase in the yield of cereals and soy by 15–20 % [29].

The way of chernozem preparation has more significant impact on the intensity of the balance (I_b) in the soil than the type of agroecosystem proper. At the same time I_b increases in the soil with the use of by-products as fertilizers. The type of the agroecosystem has more considerable impact on I_b of nitrogen when by-pro-ducts are applied, compared to the action of the way of chernozem preparation (Table 8). Subsurface tillage promotes the restoration of the natural model of nitrogen-carbon circulation in the agroecosystems, due to which there is activation of photosynthetic activity of cultivated crops due to the renewal of drain mechanisms of carbon with the increase in CO_2 content in the lowest atmospheric layers due to mineralization of by-products of the introduced organic fertilizers in the form of manure and by-products of crop cultivation in the period of crop vegetation and the enlarged heat resources, which enhances the soil formation of chernozem towards maintaining long-term fallows. With the systematic tillage the imbalance of nitrogen-carbon circulation is accompanied with the increased mineralization of organic matter of the soil, which, in the combination with intensive mineralization of organic matter, ensures high yield with simultaneous intensification of degradation processes in the soil stratum of typical chernozem of the Left-bank Forest-Steppe of Ukraine.

CONCLUSIONS

Due to long-term intensive agricultural application the chernozem of the Left-bank Forest-Steppe of Ukraine has considerably lost natural fertility which was caused by the decrease in the level of parametric self-regulation of humus, physical and chemical, and biological states; agrophysical properties, gas, nutrition, reduction-oxidation regime and moisture regime. It led to the morphological degradation of chernozem due to the steppification of genesis and deterioration of the conditions of restoring natural fertility and realization of potential fertility of typical chernozem via its efficient form.

The restoration of natural differentiation of soil by fertility starts since the moment of revolving hunks in October–November, and in May-June of the next year the starting stage of natural differentiation of the arable layer by fertility is renewed: the upper third of the humus bedrock has a higher index of biological activity, which is several orders lower than that for surface tillage. Growing inside the soil profile and impoverishing the upper third of the humus bedrock by active (physiologically active) roots, the root system disturbs the level of chemotaxis manifestation between the root system and soil microflora. Using systematic ploughing, we "separate" the existing pool of soil microorganisms and the root system to different sides of the arable layer, which is accompanied with enhanced mineralization of humus in the surface layers of chernozem and withering of the biological activity in the lower part of the arable layer with the concentrated main mass of roots. The natural organization of biochemical processes in typical chernozem is disturbed.

Due to the launch of the biochemical mechanism of humus restoration on condition of applying zero tillage there is renewal of seasonal pulsation of humus, which is determined by the physiological activity of crops in the agroecosystem and of heterotrophic microflora, which master the set of biological, physical, physical and chemical, agrochemical, and biochemical indices. The wider the amplitude of the seasonal change in the humus content is, the closer the connection is between the genetic rhythmics of the development of agricultural crops and the restoration of informative (coding) principles of soil formation for typical chernozem in the agroecosystems.

In conditions of long-term surface tillage with mulching the field surface with postcut and after-harvest remains and non-marketable part of the yield as well as optimal introduction of mineral and organic substances, there is improvement in the moisture provision of soil formation resources, which ensures the restoration of natural fertility due to the optimization of moisture regime of the soil stratum of chernozem in the seasonal and annual cycles due to the increase in the level of hydromorphism of the soil stratum of chernozem in the summer period of vegetation of cultivated crops in the agroecosystems. The potential of moisture provision for the energy of humus-accumulation of chernozem in the agroecosystems with long-term Subsurface tillage is also improved via more efficient consumption of precipitates in both winter and summer periods, which, along with the increase in the hydromorphism level, enhances the physiological acti-vity of the roots, soil microorganisms and mesofauna due to the prolongation of the biological activity period of typical chernozem in the agroecosystems by 20–25 days.

The application of different soil preparation systems revealed the connection between the depth of carbonates location, their visible forms and the increase in hydromorphism (subsurface tillage) or intensification of xeromorphosis of soil conditions (systematic ploughing) in summer, which in the former case promotes new rich carbonate formations, changing the tonality of the color of the humus-fertilized bedrock (H + Hc) to saturated ashy white color and providing for a high level of its structure capability and mellowing, testifying to secondary accumulation of carbonates in the soil profile of chernozem due to the return of previous stages of soil formation in the agroecosystems of the Left-bank Forest-Steppe under the influence of systematic surface tillage for 10–12 cm.

With the latter typical chernozem acquires the specificities, remarkable for mycelial-calcreous chernozem due to the increase in the biogenicity of soil conditions and the accumulation of carbonates *in situ*, as well as the restoration of their seasonal migration by the soil profile. In spring there is annual presence of carbonates in the humus bedrock which gradually brings chernozem closer to surface-coagulated soil. The latter should be deemed as the process of regradation of degraded typical chernozem, which is a determining feature of the soil formation in the agroecosystems of the Left-bank Forest-Steppe of Ukraine.

The systematic application of surface tillage acts as a powerful factor of restoring the humus accumulation processes, diagnosed by the darkening of transition bedrocks ($pH_к$ and Ph_k) of the soil stratum of chernozem from the flows of humus. It occurs due to high migration capability of humic acids at the moment of their formation in conditions of increased hydromorphism of the soil stratum of chernozem in the seasonal and annual cycles. The newly formed humic acids, connected to Ca, gradually migrate through the stratum of activated carbonate eluvium to the soil-forming layer. In conditions of deep aridization of the chernozem stratum in summer and due to ploughing the newly formed humic substances dry fast and get mineralized, which decreases their migration capability by chernozem profile.

The restoration of the natural model of soil formation in the agroecosystems is ensured by the activation of photosynthetic activity of cultivated crops due to the renewal of drain mechanisms of carbon with the increase in CO_2 content in the lowest atmospheric layers due to mineralization of by-products of the introduced organic fertilizers in the form of manure and by-products of crop cultivation in the period of crop vegetation due to the enlarged heat resources. With zero tillage of chernozem and due to optimization of nitrogen-carbon circulation there is the stimulating “N-effect” and “CO_2-factor” which is related to the prolongation of the period of biological activity of chernozem and activation of physiological activity of the root systems of cultivated crops and is a basic model of extensive fertility restoration of typical chernozem in the Left-bank Forest-Steppe of Ukraine.

Agricultural crops in the agroecosystems are self-developing, auto-regulated, open systems, capable of overcoming the forces, causing the increase in entropy and forming highly regulated and dynamically stable complexes of different hierarchy. We understand the principle of Nature’s solving its informative problems at the example of preserving and transmitting the information about the structure and direction of the development of the living matter, in particular, of a plant organism, but one should agree with the fact that Nature is capable of solving its informative tasks even more complete in the issues of informative, coded mechanism of manifesting the natural soil formation in the agroecosystems.

High informative value of cultivated crops defines the direction of the development of soil medium: if their genetic information capacity is in agreement with the information capacity of the natural soil formation of chernozem, there is a process of extensive restoration of their fertility in the agroecosystems, but when the process of informative or coding development of chernozem is imposed by the agriculture system, deteriorating the manifestation of self-regulation of processes and regimes, there is a decrease in soil-restoring capability of cultivated crops. Here the direction of development of typical chernozem is mastered by anthropogenic energetic expenses, which are the basis of the very agriculture system. The main task of agriculture is to create conditions for the manifestation of autocorrelation between the information capacity of the development of cultivated crops and chernozem, *i. e*. the information capacity of the development of cultivated crops should promote the realization of a morphogenetic code (memory) of the chernozem development in the agroecosystems.

Грунтовідновна активність агроценозів та відтворення родючості чорноземів за низьковуглецевих технологій

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Мета. Дати теоретичне обґрунтування підвищення потенційної родючості чорноземів типових за систематичного застосування безполицевого обробітку через створення оптимальних для фотосинтезу ґрунтових умов та забезпечення максимальної фізіологічної активності кореневих систем сільськогосподарських культур для відновлення природних процесів ґрунтоутворення в агроценозах Лівобережного Лісостепу України. **Методи.** Польовий, лабораторний, розрахунковий, математико-статистичний. **Результати.** На підставі аналізу літературних джерел та власних досліджень (понад 30 років) виявлено, що за умов мінімального обробітку забезпечується спряженість між фізіологічними ритмами життєдіяльності сільськогосподарських культур, ритмами розкладу і синтезу гумусу, фіксацією вуглекислоти гетеротрофною сапрофітною мікрофлорою та карбонатоутворенням, яке відновлює ґрунтоутворення в агроценозах. Сільськогосподарські культури в агроценозах – це саморозвиваючі, автоврегульовані, відкриті системи, здатні долати сили, які спричиняють зростання ентропії і формують високоврегульовані, динамічно стійкі комплекси різної ієрархії. Своєю високою інформативністю і кодованістю культурні рослини визначають спрямованість розвитку ґрунтового середовища в агроценозах. Якщо генетична інформативність розвитку культурних рослин резонує з інформативністю розвитку ґрунтового середовища, то відбувається процес ґрунтоутворення або процес розширеного відтворення родючості в агроценозі. **Висновки.** Залишення та використання як органічного добрива подрібненої побічної продукції рослинництва з достатньою азотною компенсацією мінеральними добривами, що загортається у поверхневий шар чорнозему за систематичного безполицевого обробітку, моделює природний характер азотно-вуглецевого обігу в агроценозах різного типу. Відтворення природної моделі ґрунтоутворення в агроценозах забезпечується стимуляцією фізіологічної активності сільськогосподарських культур в агроценозах за рахунок запуску стокових механізмів вуглецю при зростанні вмісту CO_2 у приземних шарах атмосфери протягом вегетації культур, що повинно стати базовою моделлю розширеного відтворення родючості чорноземів типових для Лівобережного Лісостепу України.

Ключові слова: ґрунтоутворення, фізіологічна активність кореня, агроценоз, фактор CO_2, стимулювальний ефект N, карбонати.

Почвовосстановительная активность агроценозов и воспроизводства плодородия черноземов при использовании низкоуглеродистых технологий

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Цель. Дать теоретическое обоснование повышения потенциального плодородия черноземов типичных при систематическом применении безотвальной обработки вследствие создания оптимальных для фотосинтеза почвенных условий и обеспечение максимальной физиологической активности корневых систем сельскохозяйственных культур для восстановления природных процессов почвообразования в агроценозах Левобережной Лесостепи Украины. **Методы.** Полевой, лабораторный, расчетный, математико-статистический. **Результаты.** На основе анализа литературных источников и собственных

исследований (более 30 лет) выявлено, что в условиях минимальной обработки обеспечивается связь между физиологическими ритмами жизнедеятельности сельскохозяйственных культур, ритмами разложения и синтеза гумуса, фиксацией углекислоты гетеротрофной сапрофитной микрофлорой и карбонатообразованием, восстанавливающим почвообразование в агроценозах. Сельскохозяйственные культуры в агроценозах – это саморазвивающиеся, самоурегулированные, открытые системы, способные преодолевать силы, способствующие увеличению энтропии и формирующие высокоурегулированные, динамично стойкие комплексы различной иерархии. Своей высокой информативностью и кодированностью культурные растения определяют направленность развития почвенной среды в агроценозах. Если генетическая информативность развития культурных растений резонирует с информативностью развития почвенной среды, то происходит процесс почвообразования или процесс расширенного воспроизводства плодородия в агроценозе. **Выводы.** Оставление и использование в качестве органического удобрения измельченной побочной продукции растениеводства с достаточной азотной компенсацией минеральными удобрениями, которая заделывается в поверхностный слой чернозема при безотвальном рыхлении, моделируют природный характер азотно-углеродного обмена в агроценозах различного типа. Восстановление природной модели почвообразования в агроценозах обеспечивается стимуляцией физиологической активности сельскохозяйственных культур в агроценозах за счет запуска стоковых механизмов углерода при возрастании содержания CO_2 в приземных слоях атмосферы в течение вегетации культур, что должно стать базовой моделью расширенного воспроизводства плодородия черноземов типичных в агроценозах Левобережной Лесостепи Украины.

Ключевые слова: почвообразование, физиологическая активность корня, агроценоз, фактор CO_2, стимулирующий эффект N, карбонаты.

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