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Study and quantification of the internal energy of the humus and soil moisture in agrocenosis from an agroecological position

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ABSTRACT

Aridization of the soil formation conditions of chernozem in agrocenoses leads to a decrease in the implementation of the internal energy of humus during the formation of fertility categories and their expression in efficient forms. In dry conditions, with no-till cultivation, the total internal energy of humus is higher than with ploughing: in the humus horizon (0–70 cm) – 1.14–1.24 times; in the thickness of 70–200 cm – 1.15–1.28 times. Under optimal moisture conditions the total internal energy reserve during no-till cultivation in the humus horizon (0–70 cm) in relation to ploughing was 1.27–1.36 times higher; in the 70–200 cm layer – 1.21–1.35 times; in the 0–200 cm layer – 1.27–1.38 times. Under humid conditions the reserve of internal total energy naturally increased, regardless of the method of processing chernozem (the black soil): 1.06–1.23 times within the genetic horizons and the entire soil layer, where the growth was 1.11–1.17 times. In the humus horizon (0–40 cm), 1% of the humus reserve during ploughing accounted for 18.0–24.5 104 kcal·m^{-2}; with no-till treatment – 22.3–29.8·104 kkal·m^{-2}, and with shallow no-till treatment – 24.5–30.9·10 4 kkal·m^{-2} which is 1.20–1.31 times and 1.24–1.36 times higher than ploughing and this indicates the important role of the soil moisture in the humus accumulation on chernozems with different methods of cultivation and at different levels of moisture. In the humus horizon (0–70 cm), with ploughing, 1% of the total reserve of internal energy accounts for 18.6–27.2 104 kkal·m–2, with shallow no-till cultivation – 24.6–31.4 104 kkal·m^{-2}, which, respectively, is 1.18–1.32 times, 1.31–1.39 times more according to the increase in the moisture conditions.

Keywords: humus, energy, moisture supply, soil formation, ploughing, black soil.

INTRODUCTION

The state of land resources in the forest-steppe zone is particularly alarming, and degradation of chernozems is one of the biggest problems of agro-soil science and farming, which poses a threat, first of all, to agro-ecological, economic and, in general, security. The degradation of chernozems and the process of climate aridization are pushing the state of chernozems in the forest-steppe zone closer to the "point of no return". For this reason, the problem of transformation of properties and regimes of chernozems resulting from changes in natural factors and anthropogenic impacts cannot be considered sufficiently studied, which requires further comprehensive study of chernozems [Report, 2010; Balyuk and Medvedeva, 2012]. The current agroecological state of forest-steppe chernozems and the direction of soil formation processes in them are determined not only by agrocenosis factors, but also by natural and climatic changes [Medvedev et al., 2014]. The conservativeness of the chernozem profile, the dominance of humus horizon in it, hides the changes occurring as a result of its use. The reason for this is that morphologically the change is diagnosed by the growth of structure density, loss of granular structure and certain morphological features, but at the same time the boundaries of the most genetic horizons remain constant [Medvedev et al., 2014; Valkov et al., 2004].

Negative change of water-physical properties in the profile of chernozem leads to a shortage of precipitation due to limited moisture absorption in winter-spring and vegetation periods. There is formation of changing character of chernozem moistening during the growing season: periods of overwatering in spring alternate with periods of complete drying in summer. Chernozems become dependent on weather and climatic conditions and sensitive to the manifestation of degradation phenomena associated with active dehumification, covering the entire soil profile of chernozems [Medvedev, 2012; Medvedev, 2012; Ivanov et al., 2013]. In natural cenoses, forest-steppe chernozems are optimally hydrated soils of non-leaching or periodically leaching regime, having no drawbacks of soils of leaching regime and drawbacks of non-leaching moisture regime [Yang et al., 2024]. Chernozem is the most optimally moistened among soils of nonwash type of water regime [Chendev et al., 2022], i.e., humus profile of chernozem in natural conditions is a product of steppe and meadow-steppe vegetation adapted to the best use of the environment in special hydrothermal conditions [Liu et al., 2021].

Therefore, one of the most important tasks related to the problem of preventing further degradation of chernozems is the search for ways to optimize the moisture regime of chernozems in agrocenosis, using soil-protective and moisture-saving agrotechnological methods that reduce productive losses of soil moisture, promote its accumulation and conservation at the expense of precipitation of autumn-winter and spring periods during vegetation [Tararyko et al., 2021]. The energy approach during the study of natural processes, including soil formation, has recently become quite widespread, because the energy characteristic of humus, its quantitative and qualitative characteristics determine almost all agronomically valuable properties of chernozems [Egergina, 2013; Zabaluyev, 2003; Orlov, 2002; Demydenko and Velychko, 2015].

The energy approach to the quantitative assessment of internal energy accumulated by chernozem humus makes it possible to determine the energy value of humus, determine the rate of energy accumulation in it and prognose the processes of quantitative and qualitative reproduction of chernozem in agrocenoses under various agrogenic impacts. An important component of the energy state of the soil profile of chernozem is the internal energy of moisture saturation, which in combination with the internal energy of humus allows us to assess the synergy of the realization of potential fertility due to its effective form of chernozem in agrocenosis [Chernysh et al., 2012; Shibut et al., 2017].

Soil formation is a process of constant transformation of energy and substance both in natural cenoses and agrocenoses, which is manifested in the formation of the main qualitative characteristic of chernozem – natural fertility. In the scientific literature there are a number of publications on energy assessment of soil fertility, which are purely theoretical in nature, in-depth studies on the assessment of fertility on the energy basis have been carried out in insufficient quantity. Therefore, the question of energy assessment of chernozems is an urgent issue [Egergina, 2013; Orlov, 2002].

The energy of humus is 5.5 kkal·g^{-1}, and the energy of water is 55.5 kkal·g^{-1}, which is 10 times higher [Chernysh et al., 2012], i.e. moisture saturation is a more effective factor in increasing the internal energy of chernozem than the humus content, and the ratio of internal energy of moisture to internal energy of humus can characterize the efficiency of humus energy output when realizing the potential fertility because of its effective form: the wider the ratio, the higher the energy output of humus, and when narrowing, on the contrary, the energy supply of humus reproduction decreases.

The relevance of the work lies in the need to establish the energy of interaction of the humus accumulation regime with the moisture regime of chernozems with long-term use of ploughing, compared to the soil conservation cultivation, based on systematic use of no-till cultivation and the establishment of a synergistic interaction of the humus accumulation energy and hydrophilitization to accelerate the deposition of the organic matter in humus, which will determine the ways to stop the chernozem dehumification.

The aim of the research is to determine, based on a quantitative assessment of the internal energy accumulated by humus, its relationship with the energy potential of active moisture in the soil layer at different degrees of soil hydrophilization, and also to assess the level of manifestation of synergism between the energy of humus and moisture depending on the methods of soil cultivation in agrocenoses.

MATERIALS AND METHODS

The criterion for choosing the location of the research was the location of the objects in the latitudinal dimension of 49027-57´17-20´´ north latitude and 35007-57´50-55´´ east longitude. The difference in altitude above sea level along the longitude was 25 m, which determines the proximity of the research objects in terms of humification rates for different subtypes of chernozems with different levels of humus content and granulometric composition.

The research methodology was based on a working hypothesis that assumes a synergistic enhancement of the humus accumulation process and hydrophilization of the moistening regime with systematic implementation of soil protection cultivation in agrocenoses, which affects the growth of total energy in the chernozem layer, as a criterion for reproducing the fertility of chernozem.

To solve the problem, methods were used to determine the content of total humus, moisture reserves and calculate energy reserves in humus and moisture reserves in the soil layer.

The study of long-term effect of no-tillage on fertility restoration of typical chernozems in agrocenoses of forest-steppe Left-bank physiographic province was carried out under the following conditions: soil cover within the southern part is represented by typical chernozems (> 50%) with medium humus (5.55–5.65%). According to the content of physical clay (PC) and physical sand (PS), chernozem can be referred to light clay: PC = 62.9–64.0% and PS = 35.0–37.1%. Such technological indicators on granulometric state are typical for typical chernozems.

The research was also conducted on typical low-humusified light loamy silt-dusty chernozems. The structural index (SI) is: PS = 25–38%. The ratio of PS to PC: 1.76–2.52, which is 3.2 times higher compared to typical medium-humusified light loamy chernozem. Factor of potential aggregation (FPA): FPA = 0.25–0.27, which is 2.78–2.96 times lower than in typical medium-humus light loamy chernozems. Studies were also conducted in multifactorial stationary experiment in the link (sugar beet – peas – winter wheat – grain corn – silage corn) of the southern part of the forest-steppe (cereals – up to 40%, technical – up to 30%, leguminous – up to 10%, forage – up to 20%), where 4 methods of soil cultivation were studied: multi-depth ploughing (22–32 cm), no-tillage multi-depth ploughing (22–32 cm), shallow no-tillage (10–12 cm). In the crop rotation was applied: 15 t·ha^{-1} by-products + $N_{85}P_{75}K_{65}$ (average dose).

Stationary experiment was still conducted in multifactorial stationary experiment in which two types of 5-field crop rotations were studied: A: perennial grasses – winter wheat – sugar beet – corn – barley + perennial grasses (cereals – up to 60%, technical – up to 20%, perennial grasses – up to 20%). Methods of basic tillage: multi-depth ploughing (22–25 cm) for all crops; no-tillage (22–25 cm) for all crops; surface tillage (8–12 cm) for all crops. The crop rotation was applied: 6–7 t·ha^{-1} of by-products + $N_{82}P_{65}K_{65}$. To determine changes in water-physical parameters and moisture regime, samples were taken from soil layers 10 cm apart according to the schemes of experiments. Soil samples were analyzed, recorded and calculated in accordance with special methods: moisture content – by thermogravimetric method for the main periods of crop growth; moisture reserves – calculated to the depth of 150–180 cm. Total humus content – according to Tyurin in modification of Simakov (DSTU 4289:2004). References [Chernysh et al., 2012; Shibut et al., 2017] were used to calculate the internal energy of total humus and the range of active moisture of chernozems:

The internal energy reserve of total humus in chernozems is calculated by the formula:

$$P_{e.h.} = S \cdot H \cdot D \cdot C_h \cdot 5.5, \text{ kkal·g}^{-1} \quad (1)$$

where $P_{e.h.}$ – internal energy of total humus in the 0–180 cm thickness per 1 m^2, kkal, S – square, cm^2; H – soil thickness, cm; D – structural density, g·cm^{-3}; C_h – total humus content, %, 5.5 – humus energy, kkal·g^{-1} [Chernysh et al., 2012].

The internal energy reserve of soil moisture in chernozems is calculated by the formula:

$$P_{e.v.} = S \cdot H \cdot D \cdot C_v \cdot 55.55, \text{ kkal·g}^{-1} \quad (2)$$

where: $P_{e.v.}$ – is the internal energy of available moisture in the 0–180 cm thickness per 1 m^2, kkal; S – square, cm^2; H – soil thickness, cm; D – structural density, $g \cdot cm^{-3}$; C_v – productive moisture content, %; 55.55 – water energy, $kkal \cdot g^{-1}$ [Chernysh et al., 2012].

The given analytical expressions (1) and (2) were used by us when carrying out the corresponding calculations on a PC, when the quantities included in them were determined by us on the basis of long-term field experimental studies.

The provided analytical expressions (1) and (2) were used by us when carrying out the corresponding calculations on a PC, when the quantities, included in them, were determined by us on the basis of long-term field experimental studies.

Generalization of indicators of moisture regime and content of total humus of chernozem and calculations of research results were carried out according to the "Method of dispersion analysis" using the program "STATISTICA" and the use of non-parametric methods of statistics, correlation analysis.

RESULTS AND DISCUSSION

During ploughing under conditions of insufficient moisture content the redistribution of field moisture is close to WP (wilting point), at optimum moisture content it is at the level of crop stunting moisture, and at optimum moisture content in the 0–70 cm thickness at the level of EM-CBM, from the depth of 70 cm moisture content is below the capillary breakage moisture content. Under deep no-tillage cultivation, the distribution curves of field moisture in the profile of chernozem under drought, optimal and sufficient moistening gravitate to the capillary fracture moisture to a greater extent, and the curve corresponding to a high level of moistening is between EM-CBM, but gravitates to the capillary fracture moisture. Under shallow no-tillage cultivation, the wetting distribution curve in the profile corresponding to drought conditions is maximally close to the capillary rupture moisture, and under optimal and excessive wetting is at the level of capillary rupture moisture, from the lower part of the profile exceeds capillary rupture moisture, and under excessive wetting, to a greater extent, gravitates to EM (excessive moisture) (Figure 1).

The increase of the degree of typical chernozem hydromorphism under conditions of systematic application of soil-protective technologies in crop rotation has its theoretical substantiation. In April, under systematic application of deep ploughing in crop rotation, there is a process of soil moisture saturation to EM values and to a deeper depth in comparison with systematic no-tillage at different depths. In connection with this circumstance, soil moisture has a higher mobility during spring ploughing, and moisture turnover is activated in a significant thickness of the profile.

Capillary moisture moves to the evaporation surface – stationary capillary flow occurs and thermodynamic equilibrium is established between the amount of evaporated capillary moisture and the amount coming from deeper soil layers. The higher the degree of soil profile saturation with moisture and the deeper it is observed, the longer in time the action of stationary capillary flow to the evaporation surface appears. The action of capillary flow stops when the capillary breaking moisture (CBM) in the chernozem profile is reached. Two mechanisms of moisture transport begin to show simultaneous action under the CBM: capillary, directed against the moisture content gradient, and convection-diffusive, when moisture is transported in the form of vapor along the wetting front deep into the soil column. The simultaneous action of capillary and convection-diffusive transport should be considered as the emergence of a nonlinear dissipative system, which is in a state of thermodynamic equilibrium violation. During the growing season of field crops, the ratio of the share role of different moisture transport devices tends to favour the convection-diffusion mechanism. Relative undersaturation of chernozem with moisture at the depth of the second meter in spring under no-tillage promotes the inclusion of convection-diffuse mechanism of moisture transfer earlier than under ploughing. At a depth with constant humidity and temperature, water vapor liquefies and begins to rise again to the evaporating surface, reaching a depth of 130–140 cm from the soil surface at the time of the beginning of the critical phase of crop development in late June to mid-July.

In the variant with systematic ploughing, similar processes begin to appear a little bit later. And moisture, which descended deep into the soil

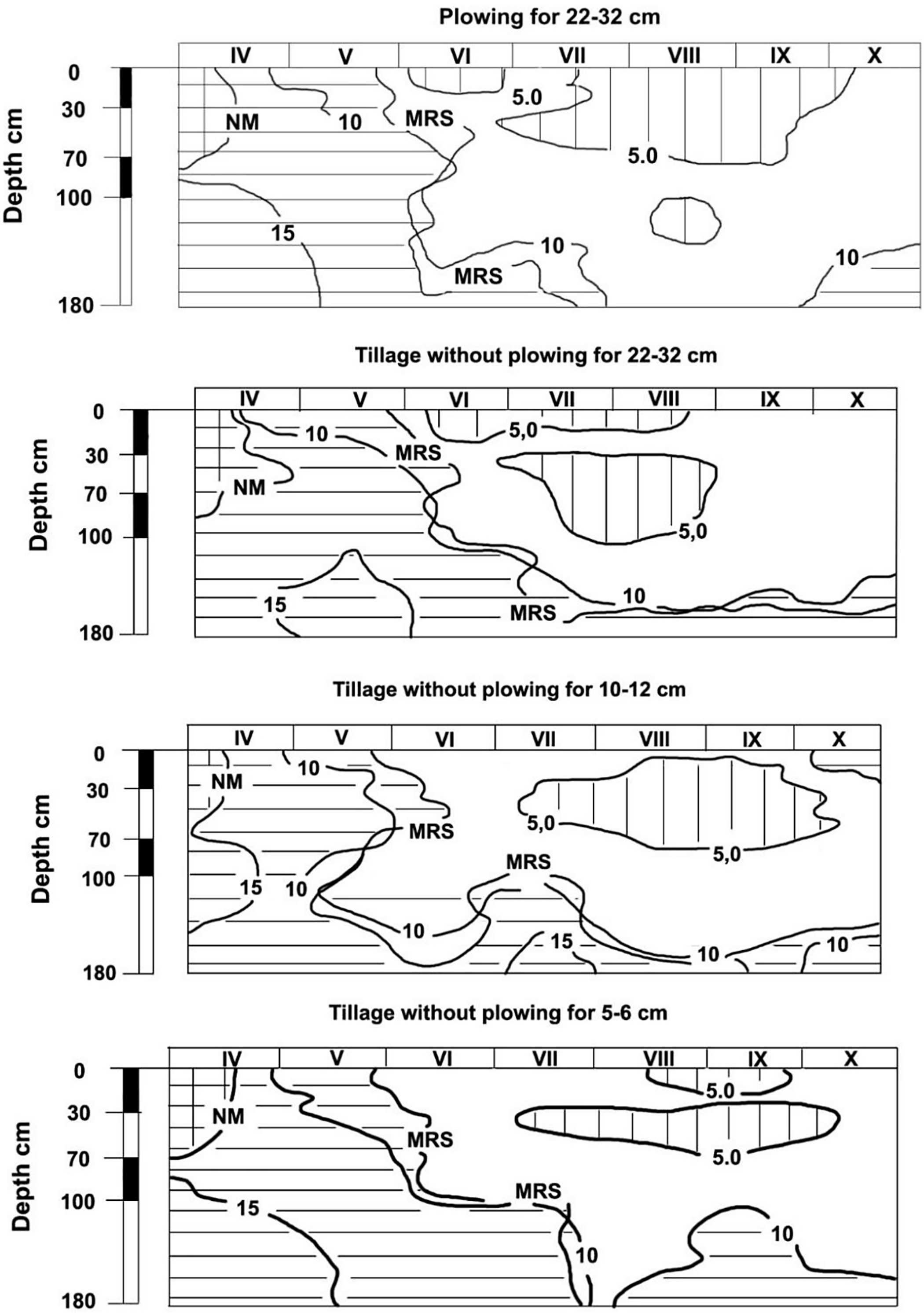

Figure 1. Influence of treatment method of typical chernozem on the dynamics of productive moisture reserve

profile in the form of water vapor, condenses at a much deeper depth due to the greater porosity of the soil profile. Due to this circumstance, liquefied moisture does not have time to rise to the level that is achieved under no-tillage conditions, so crops spend significantly more energy resources on root growth to reach depths in the soil with available moisture. Excessive growth of the root system during critical phases of plant development is usually associated with reduced yields.

Optimal moisture saturation of the soil profile of typical chernozem in spring under systematic application of soil-protective technologies, more perfect construction of humus horizon, weighted water-uplifting and water-saving capacity contributes to an increase in the degree of hydromorphism of typical chernozem as an automorphic system, and simultaneous functioning of capillary and convection-diffuse mechanism of moisture transfer contributes to the formation of moisture turnover of optimal moisture supply at all stages of plant development. In our opinion, this type of moisture turnover should be called optimized according to the principles of soil body self-organization.

The research has established that in April, regardless of the tillage method, the same productive moisture reserves in 0–180 cm of soil thickness were formed, which, depending on the year conditions, varied in the range of 165–240 mm, and in the meter thickness – 130–170 mm. However, in July the long-term influence of different tillage methods on productive moisture reserves in 0–180 cm of chernozem thickness was revealed. Under systematic ploughing the moisture reserves were 95–180 mm, while under no-tillage and surface tillage they were higher by 5–10 mm and 20 mm according to the treatments. In the meter thickness of chernozem the established regularity was preserved (Figure 1).

Long-term implementation of no-tillage and surface tillage provided 15–25 mm increase of productive moisture reserve. At systematic ploughing, the productive moisture reserve consumption for the period April-July was the highest: 106–122 mm (0–100 cm layer of soil) and 90–100 mm (0–150 cm layer of soil), while at no-tillage and surface tillage the moisture consumption for physical evaporation and transpiration from 0–100 cm thickness was lower by 10 mm and 21 mm, respectively, and from 0-150 cm thickness – by 5–20 mm. Expenditure of productive moisture reserve according to typical boundary values with decreasing tillage depth decreased in 0–150 cm thickness by 20 mm relative to ploughing. In September, irrespective of the method of chernozem tillage, no significant difference in moisture reserves in the meter thickness of chernozem was detected (79.0–82.0 mm). Significant difference in productive moisture reserves was detected at minimum type values: at surface tillage in 0–50 cm layer of soil thickness moisture was 21 mm more, and in general in 0–100 cm thickness moisture reserves were the same compared to ploughing and no-tillage treatments.

At surface tillage (April–July) moisture was spent 1.2 times more efficiently than at systematic ploughing, and in general for the period April-September 1.12 times more efficiently than at ploughing. At deep tillage more moisture was spent (62–65%) from total expenses in spring-summer period, whereas at surface tillage the consumption of productive moisture reserve was more uniform during spring-summer-autumn period. There was hydrophilization of soil conditions in summer. Regardless of moisture conditions, the internal energy of humus under different tillage systems was close for genetic horizons of chernozem (0–70 cm, 70–200 cm and 0–200 cm).

Under drought conditions, the internal energy was $185 \cdot 10^4$ kkal·m^{-2} higher in the humus horizon (0–70 cm) under no-tillage, $153 \cdot 10^4$ kkal·m^{-2} higher in the thickness of 70–200 cm, and 252 kkal·m^{-2}, 360 kkal·m^{-2} and 607 kkal·m^{-2} higher in the layers of soil thickness, respectively. At the same time, soil moisture energy was higher than humus energy by 27, 130 and 55 times (ploughing); by 32, 150 and 68 times under no-tillage; by 35, 160 and 73 times under shallow no-tillage. Under conditions of optimal moistening, the internal energy of moisture supply during ploughing increased by 1.33, 1.11 and 1.25 times, respectively, for layers of chernozem 0–70 cm, 70–200 cm and 0–200 cm. At no-tillage the increase was 1.17, 1.20 and 1.18 times, and at shallow no-tillage – 1.13, 1.33 and 1.17 times (Figure 2).

At that, the internal energy of soil moisture increases at ploughing by 36, 130 and 67 times relative to humus energy; at no-tillage – by 36, 170 and 78 times, and at shallow no-tillage – by 38, 190 and 84 times, respectively, for soil layers 0–70 cm, 70–200 cm and 0–200 cm.

Similar increase of internal energy is observed in wet conditions, and moisture energy exceeds humus energy 44–47 times (0–70 cm). In 170 times in the thickness of 70–120 cm under ploughing and in 190 times under no-tillage, and in the thickness of 0–200 cm in 79 times under ploughing and in 92–93 times under no-tillage. It should be noted that the total internal energy of humus and moisture by 80–99% is determined by the internal energy of soil moisture, which indicates the determining role of moisture in the realization of energy reserves in humus.

Aridization of conditions in the soil profile leads to a decrease in the level of realization of internal energy of humus in the formation of chernozem fertility categories and their realization through the effective form. Under arid conditions from ploughing to shallow no-tillage the total

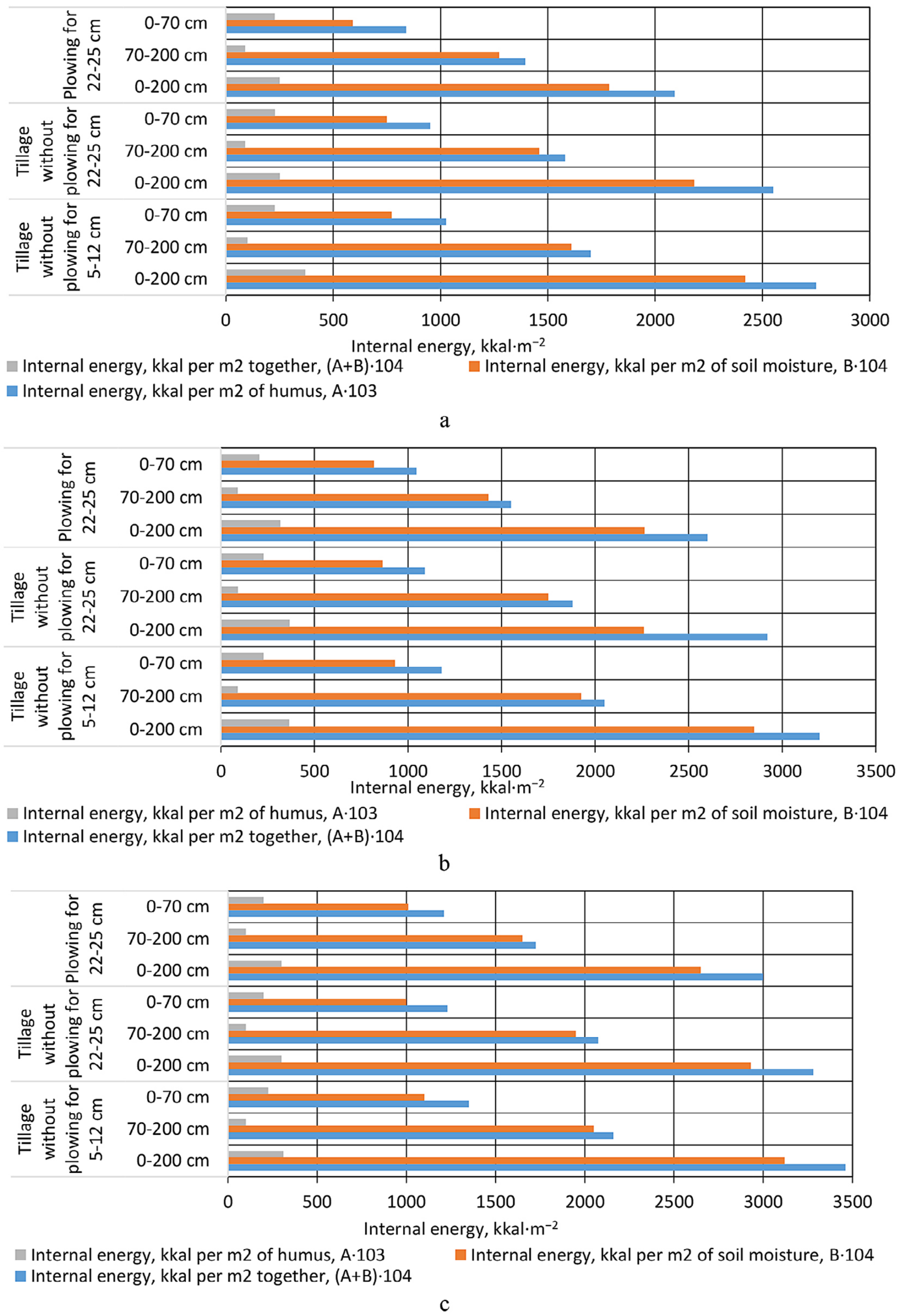

Figure 2. Long-term effect of different treatment methods on internal humus and moisture supply energy reserve in agrocenosis of the forest-steppe zone: a – arid moistening conditions; b – optimal moistening conditions; c – excessive moistening conditions

internal energy increases: in the humus horizon (0–70 cm) – 1.14–1.24 times, in the thickness of 70–200 cm – 1.15–1.28 times, and in the thickness of 0–200 cm – 1.21–1.33 times. Under optimal moisture conditions, the total internal energy reserve under no-tillage with respect to ploughing in the humus horizon (0–70 cm) the reserve of total internal energy under no-tillage was higher by 1.27–1.36 times, and in the thickness of 70–200 cm – 1.21–1.35 times, in the thickness of 0–200 cm – 1.27–1.38 times.

Under wet conditions of moistening, the stock of internal total energy increased naturally regardless of the method of cultivation of chernozem in agrocenosis: in 1.06–1.23 times within genetic horizons and the whole soil layer, where the growth was in 1.11–1.17 times. The general regularity was that with increasing moisture level the reserves of total internal energy, irrespective of tillage method, were equalized by absolute value, but remained higher under no-tillage and increased in the direction of minimum tillage.

It should be noted that regardless of the moisture level and tillage method, the stock of total internal energy in the 70–200 cm layer was at the level of 62–67% of the total in the 0–200 cm layer. However, under no-tillage cultivation the stock of total internal energy was higher due to saturation of 70–200 cm thickness with soil moisture. For 1% of total internal energy, ploughing had 20.0–26.7·10^4 kkal·m^{-2}, no-tillage had 22.5–26.7·10^4 kkal·m^{-2}, and no-tillage shallow cultivation had 24.4–31.4·10^4 kkal·m^{-2}, which were 1.13–1.22 times, 1.20–1.33 times, and 1.10–1.17 times higher than ploughing in accordance with increasing moisture conditions.

In humus horizon (0–70 cm) at ploughing per 1% of total internal energy reserve there are 18.6–27.2·10^4 kkal·m^{-2}, at shallow no-tillage cultivation – 24.6–31.4·10^4 kkal·m^{-2}, that, respectively, in 1.18–1.32 times, 1.31–1.39 times more in accordance with the increase of moistening conditions. In humus horizon (0–40 cm), per 1% of the reserve at ploughing was 18.0–24.5·10^4 kkal·m^{-2}, at no-tillage – 22.3–29.8·10^4 kkal·m^{-2}, and at shallow no-tillage – 24.5–30.9·10^4 kkal·m^{-2}, which is higher by 1.20–1.31 times higher and 1.24–1.36 times higher relative to ploughing, and this indicates the importance of soil moisture in humus accumulation on chernozems under different tillage methods and at different moisture levels.

On typical medium humus medium loamy chernozems (central part of the left-bank forest-steppe) the application of no-tillage for 25 years contributed to the reproduction of humus energy reserves in the humus horizon by 6.9–12.1%, and in the transitional HPK (upper transitional carbonate) horizon (70–90 cm) – by 16%. In the Phk (lower transitional carbonate) horizon (90–100 cm) – by 18–19%. In the transitional horizons (HPк and Phк) the reduction of energy in humus at ploughing of undisturbed soil for 54 years amounted to 19–25%, and reproduction at long-term (15–25 years) application of no-tillage restores humus energy reserve by 16.0–18.5%.

The content of chernozem in the overlog state for 17 years indicates that the humus energy reserve of 20.6–25.4% is reproduced in the soil layer of 40–90 cm. Systematic application of no-tillage cultivation for 25 years provides reproduction of humus energy not lower than that of chernozem in the fallow state. Estimation of the rates of facial humus accumulation on chernozems of the left-bank forest-steppe was carried out by calculating the coefficients of facial humus accumulation strengthening ($K = J_g{:}J_y$).

It was revealed (Table 1) that the rates of facial accumulation of humus increase 6.7 times in zonal measurement from the northern part of the forest-steppe zone to the strip of separation of the steppe and forest-steppe zones, and further to the south the rates of facial accumulation of humus decrease 2.7 times. The amount of energy in humus increment from application of no-tillage during 10 years exceeds the stock of energy in yield increment, which indicates the reproduction of natural processes of soil formation in agrocenoses in zonal dimension.

Synergetic weighting of humus energetics with soil moisture is provided when moisture content in the chernozem stratum does not decrease to the WP values and to a greater extent is manifested

Table 1. Change of coefficients of strengthening of facial humus accumulation in agrocenoses of forest-steppe zone from application of no-tillage cultivation

Climate zone	Energy reserve after 15 years of applying soilless cultivation in increments		Δ $J_g - J_y$	Facial humus accumulation enhancement coefficient, $K = J_g{:}J_y$
	yield, J_y	*humus, J_g		
	million kkal. per 1 ha			
Northern part of the central forest-steppe zone	390·10^4	1120·10^4	+730·10^4	**3.0 / 100
Southern part of the forest-steppe zone	250·10^5	500·10^6	+475·10^6	20.0 / 665
Central and southern part of the steppe zone	750·10^4	555·10^5	+480·10^5	7.4 / 243

Note: *thickness of chernozem 0–100 cm; **K/%.

in the moisture interval: plant wilting moisture (PWM) – capillary breaking moisture (CBM) – 75% EM. The study of the influence of different tillage systems on the moisture saturation of the soil thickness of chernozems showed that the constant implementation of no-tillage with a steady tendency to minimize tillage leads to the fact that the moisture saturation in the thickness of 0–100 cm and 100–200 cm in the driest period of summer is within the specified limits, while with systematic ploughing it decreases to the values of WP.

The integrative nature of the interaction of elementary volumes of compressed air is expressed in a change in its thermodynamic state through the movement of the generalizing soil meniscus, which leads to self-oscillating thermodynamic processes and is the essence and motive force of the process of self-regulation of the soil processes in the thickness of chernozem under conditions of systematic implementation of soil-protective cultivation. The result of cultural soil formation in agrocenoses depends on the duration of the specified state of chernozem during the growing season. When ploughing, the permanence of soil formation in agrocenoses is disrupted by drying out of the chernozem layer in the period June-August, whereas with no-till cultivation, increased biogeneity in the black soil layer is ensured throughout the entire growing season [Shibut et al., 2017].

During plowing and deep no-till cultivation, the agrophysical state of the 0–30 cm layer of chernozem is determined by hydrothermal conditions and the amount of precipitation during the warm period of the year, which indicates aridization of soil conditions and the manifestation of agrophysical degradation. During ploughing and deep no-till cultivation the agrophysical state of the 0–30 cm layer of chernozem is determined by hydrothermal conditions and the amount of precipitation during the warm period of the year, which indicates aridization of soil conditions and the manifestation of agrophysical degradation. In conditions of systematic ploughing to a greater extent, and deep no-till cultivation to a lesser extent, the realization of natural and efficient fertility and productivity of agrocenosis depends on the state of climatic factors. With shallow no-till cultivation chernozem becomes autonomous, and potential and effective fertility is not limited in its implementation, which determines the level of productivity of the agrocenosis and the conditions for expanded reproduction of the chernozem fertility [Gang et al., 2007; Briedis et al., 2023].

Under conditions of no-till cultivation, a stable connection arises between the intensity of external conditions and the chernozem dissipativity, ensuring the subordination of local self-regulation processes in the agrocenosis: the activity of the kinetic soil environment of chernozem is stabilized. The range of the thermodynamic state, limiting the homeostatic plateau of chernozem resistance to the components of the external environment in the range of moisture, available to the plants, is determined by the irregularity of the intersection of the borehole space, and this state is a fundamental property of chernozem, ensuring the irreversibility of the action of the cyclic components of external flows of energy and matter [Briedis et al., 2023; Koković et al., 2021].

Systematic implementation of the soil-protecting no-till tillage helps optimize the moisture regime in agrocenoses. The optimization of the moisture regime is based on an appropriate and balanced ratio of the simultaneous action of the capillary and convection-diffusion mechanisms of the soil moisture transfer, which ensures a higher content of the productive moisture in the thickness of the chernozem in critical phases (mid-summer) of the development of agricultural crops in agrocenoses.

Reproduction of natural soil formation in agrocenoses should be perceived as strengthening of a combined effect of the biological factor of soil formation due to the strengthening of the synergetics of the implementation of the ecological potential of humus and hydrological soil conditions in seasonal and annual cycles under the influence of the systematic use of soil-protection technologies, based on no-till cultivation, which ensures strengthening the process of energy management of the functional-ecological and the facies patterns of humus accumulation in chernozems, typical in agrocenoses.

The growth of hydromorphism (he growth of the energy of hydrophilization) of the chernozem layer during no-till cultivation is necessary to provide conditions for increased activity of the root systems with the aim of deep saturation of the chernozem layer with a root exudate (ensuring the energy of the humus accumulation) and ensuring the water-soluble state of pre-humus substances at the time of their new formation. There is constant deep saturation (to the depth of regular moisture wetting of the soil profile of chernozem in spring) with humic substances.

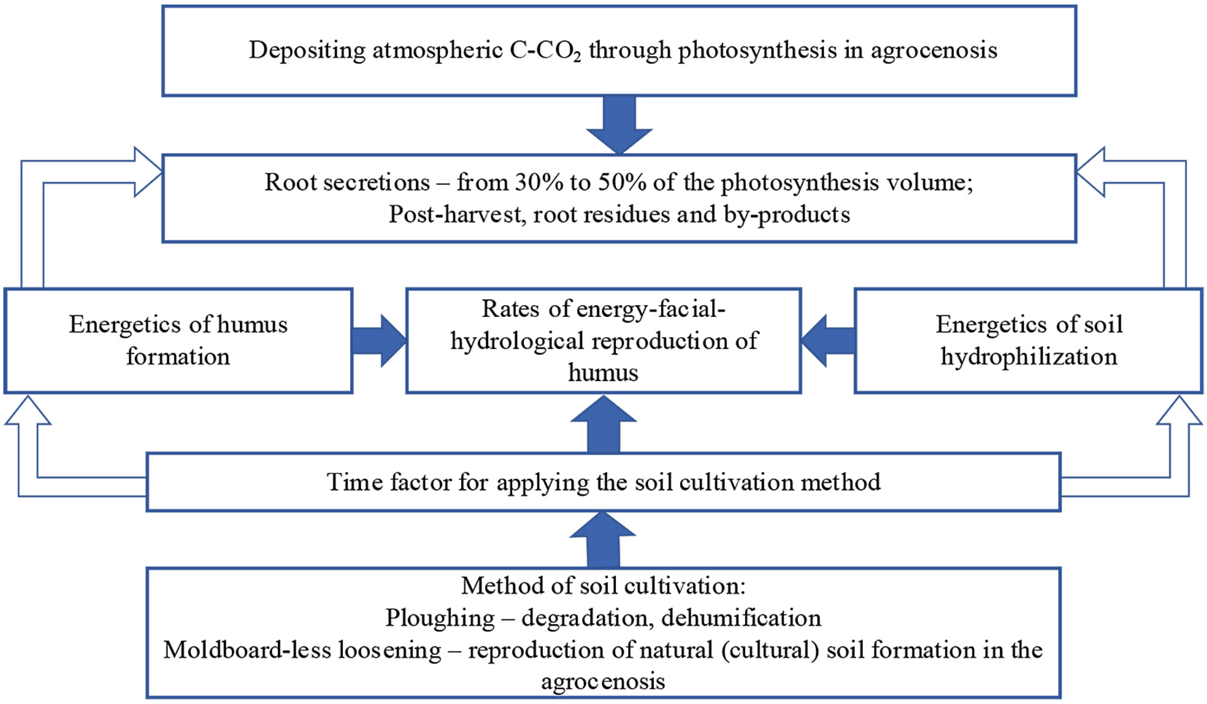

Figure 3. Scheme of interaction of the process of atmospheric C-CO_2 deposition, synergism of the energetics of humus formation and strengthening of soil hydromorphism on the rate of facies-hydrological reproduction of humus under the influence of soil cultivation

Cultural soil formation is an increase in the interaction of the carbon monoxide deposition by agrophytocenoses of cultivated plants with the process of the humus formation activation in the root rhizosphere and the restoration of natural soil formation in agrocenosis, which should be perceived as a manifestation of the sod process intensification under the influence of biologization of the soil conditions and an increase in the functional-agroecological conditions of the facial patterns of saturation of the chernozem profile with a physiologically active root exudate of cultivated plants under the influence of the systematic use of soil-protective soil cultivation.

A comparison of the available information on the deposition of the atmospheric carbon dioxide through photosynthesis by agrophytocenosis, humus formation in the root rhizosphere and soil formation in the agrocenosis provides grounds for the conclusion that all these processes are closely related to each other ($R = +0.78 - 0.84 \pm 0.02$; $R^2 = 0.61 - 0.71$). A schematic representation of the interaction of the processes under consideration is shown in the figure, from which it is evident that photosynthesis, humus formation and cultural soil formation should be considered as structural components of a complex system that synergistically interact with each other and cumulatively accumulate under the influence of the time factor (Figure 3).

CONCLUSIONS

The intensification of he chernozem formation processes in agrocenoses is significantly influenced by the hydrophilicization of the moisture regime, which is ensured within the framework of the periodically leached water regime of the soil cultivation system. The realization of the internal energy of humus is possible only in a balanced relationship with the energy of the soil moisture. The energetic synergy between humus and the soil moisture determines the efficient realization of the natural and potential soil fertility. As the share of the moisture energy increases, compared to the humus energy, the fertility potential improves significantly, especially promoting the renewal of the soil formation processes.

Under drought conditions and in the event of a decrease in the moisture energy, the humus mineralization increases, which causes a decrease in the fertility level of chernozem. Systematic no-till soil cultivation provides a greater total internal energy storage in the long term, compared to the traditional tillage — especially in the deeper layers of the profile (70–200 cm), indicating a more sustainable renewal of the humus reserve. More than 80–90% of the total internal energy of chernozem consists of the soil moisture energy, which confirms the crucial role of moisture in the use of the humus energy. A synergistic interaction between plant exudates, moisture transport mechanisms, and the humus formation was observed, indicating an enhancement of cultivated soil formation in the agroecosystem.

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