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Seasonal sequestration capacity of chernozem under different agrotechnological impacts in agrocenosis

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Abstract. The soil's sequestration capacity is primarily determined by the fine-dispersed fraction of the soil and strongly influences the properties and fertility level of the soil. To assess the sequestration capacity of C-CO_2 humus in soil formation and fertility of typical chornozem (black soil), to identify the causes, rates, existing limits of the sequestration capacity decrease, it is important to study the seasonal dynamics of qualitative and quantitative indicators of humus state in time depending on the method of tillage and fertilization in agrocenoses of short rotation crop rotations in the central part of the Forest-Steppe region of Ukraine. During the research, a stationary field experiment was conducted to study the influence of methods of soil cultivation and fertilizer application on the sequestering capacity of chornozem. Laboratory studies were conducted to determine the content of humus and to calculate the seasonal reserves of absorbed carbon and phosphorus and to model the absorption capacity of chernozem. When processing with chisel plows and applying fertilizers, the increase in the C-CO_2 reserve during the April-July period was +21 t ha^{-1} (0–0.2 m) and +36 t ha^{-1}a (0–0.3 m). Under moldboard plowing, the growth tended to increase by 1.52 times (0–0.2 m) and 1.25 times (0–0.3 m), but occurred at a lower quantitative level, and in the period July-September, the change in the humus C-CO_2 stock was insignificant, indicating the predominance of C-CO_2 sequestration processes in the summer-autumn period with chisel plowing. With chisel plowing, the reserve of labile organic substances (LOS) in April exceeded the stock for plowing in the thickness of 0–0.3 m by 4.34–7.67 times (without fertilizers), 1.5–2.76 times (with fertilizers); in July - by 4.59–8.90 times (without fertilizers) and 1.32–3.16 times (with fertilizers); in September - by 4.52–4.04 times (without fertilizers) and by

1.11–1.93 times (with fertilizers), and the C-CO_2 stock of the LOS compared to fallow land under chisel plowing without fertilizers in April, July, and September was 1.59–1.78 times, 2.31–3.29 times, and 1.4–1.78 times higher, and under fertilization - by 1.99–2.0, 1.86–4.50, and 1.7–2.6 times, respectively, depending on the seasons. Under fallow land maintenance, the seasonal dynamics of the C-CO_2 stock of the LOS is subject to the seasonal dynamics of $P_{org(LOS)}$. A direct strong correlation was found at the level of R = +0.89 ± 0.02; R^2 = 79. In the period April-July, the decrease of $P_{org(LOS)}$ stock in the thickness of 0–0.2 m was found to be 1.15 times, and in the thickness of 0–0.3 m - 1.1 times. From summer to autumn, the stock of $P_{org(LOS)}$ was restored, and the stock in the thickness of 0–0.3 m increased by 1.10 times. Conclusions. Trends in C-CO_2 stocks of humus and LOS indicate that in the series plowing-chiseling-fallow land, the cyclicality index under chisel plowing was closer to the value of the seasonal cyclicality of fallow land than the seasonal cyclicality under plowing, which indicates the restoration of the CI. Trends in C-CO_2 stocks of humus and LOS indicate that in the series plowing-chiseling-fallow, the index of cyclicality under chisel plowing was closer to the value of the seasonal cyclicality of fallow land than the seasonal cyclicality of plowing, which indicates the restoration of the I_{SC}. However, the timing of changes in the $P_{org(LOS)}$ stock indicates that in the series plowing-chiseling-fallow, chisel plowing is directed to fallow land by its seasonal cyclicality. The general regularity of seasonal cyclicality for all parameters of humus condition lies in the fact that a decrease in the values of I_{SC}, as in fallow land or under moldboardless tillage, indicates the ordering of I_{SC}, and an increase in the index of cyclicality to destruction, as under plowing.

Key words: organic carbon and phosphorus stocks, plowing, chisel plowing, trends in stock changes, light-hydrolyzable organic matter.

INTRODUCTION

The majority of arable lands in Ukraine are covered by fertile black soil, known as 'chornozem' in Ukrainian, which translates to 'black earth'. The conclusion of Academician Volodymyr Medvedev (2007) regarding the degradation of arable chornozem soils in Ukraine under modern agricultural practices, along with the notion that '…soil-forming processes can develop in two directions - natural, which forms a typically genetically determined soil, and anthropogenic, which forms degraded soil (due to a constant deficit balance of biogenic elements and unregulated, almost uncontrollable compaction) with parameters differing from natural ones…' holds true. Chornozem soils in agrocenoses, as a 4-dimensional polygenic formation (Medvedev, 2016), undergo anthropogenic transformations into degraded formations, and the cumulative technogenic and anthropogenic loads exceed the chornozems' capacity for self-reproduction and self-regulation of soil fertility.

In nature, ecosystems create a self-regulating mechanism, with plants and soils as the key components that accumulate solar energy in the form of living matter (biomass) and soil humus. The integrating indicator of these processes is the system of humic substances in the soil (Bardgett et al., 2014). Chernozem soils are characterized by a transformation-migration type of humus profile, representing a self-regulating system. The upper part (approximately 0.2 m) of this profile possesses a transport function within the upper zone of the humus profile of chernozem soils (Hirte et al., 2017). The humus horizon of chernozem soils is a mandatory condition for the formation and evolution of chernozems. Consequently, the functioning processes of the humus horizon determine the direction and intensity of elementary typogenetic processes in chernozem soil formation (Philippot et al., 2013).

Nature has developed a complex and organically reasonable adaptation for plants to acquire mineral nutrients - the process of humus formation, and in a broader sense, the process of soil formation. During the cultivation process, the biochemical ‘pulsation’ of the humus horizon in chernozem soils is nearly halted, causing the soil to lose its chemical and physical properties and transform into a more or less inert substrate. Under conditions of high fertilizer doses and intensive cultivation, it becomes challenging to achieve high yields on such soils (Torma et al., 2017).

In arable agroecosystems, irregular fluctuations significantly increase compared to natural biogeocenoses, and the amplitude of the seasonal cyclicality of the soil solution is markedly reduced. This is primarily explained by the absence, in the upper layer of arable chernozem soils, of the necessary supply of dead organic matter in the form of a substantial layer of steppe litter (Shykula & Demydenko, 1998). The role of harvested root residues and by-products is particularly crucial in modern farming conditions, emphasizing the importance of the creation and application of machinery for their removal (Bulgakov et al., 2017; Bulgakov et al., 2020; Bulgakov et al., 2022b).

Only the restoration of rational seasonal cyclicality in chernozem soils can lead them to a specific stable state, and the biologization of agriculture is the most promising direction that ensures the preservation of chernozem fertility and increased profitability of cultivated crops. A significant role is assigned to crop rotation saturation with crops designed to enrich the soil with organic matter and nitrogen, mobilize inaccessible forms of phosphorus and potassium, and improve the soil's water-physical properties (Philippot et al., 2013). To reduce soil compaction and structure destruction, special attention should be given to the use of wide-capture or bridge-type implements (Ivanovs et al., 2020; Bulgakov et al., 2022a).

The content of total humus, both in virgin and arable chernozem, decreases from spring to summer. By autumn, it increases again, striving to reach the initial level and even surpasses it in November when chernozem is covered with snow, and the restorative processes sharply prevail over oxidative ones or completely suppress them. The idea of organic matter as a conservative formation is erroneous, as established by numerous researchers (Dehtyarov et al., 2012; Demydenko & Velychko, 2015; Kachmar et al., 2019).

The noticeable decrease in humus content from spring to summer is attributed to the intensification of oxidation processes under optimal conditions of moisture and temperature. During the summer, oxidative processes sharply prevail in the soil, while with increasing moisture in the fall and spring, restorative processes become predominant. The reduction in pH during the summer period can weaken the bonds between humus and the mineral part, thus impairing the soil's aggregating capacity. (Balayev et al., 2020; Volkohon & Moskalenko, 2020). However, it simultaneously enhances the mobility of nutrients and improves the nutritional regime of chernozem. There are periods during spring, summer, and autumn, or even individual years, when there are predominantly losses or gains in humus content in soils. The temporal disparity in the processes of humus formation or decomposition is linked to hydrothermal conditions and the intensity of microbial activity, influencing these processes and being influenced, in turn, by cultivation practices (Balayev et al., 2019; Shykula et al., 2000).

Research by B.S. Nosko (Nosko et al., 2008; Nosko et al., 2010; Nosko & Gladkih, 2012; Nosko, 2017) has established that organic phosphates are one of the main reserve fractions of phosphorus. Their content should be considered as a ratio of mineralization processes and the synthesis of organic matter, including humus and labile organic substances (LOS). This underscores the significance of organic phosphates in the soil formation of chernozems. The content of organic phosphates is closely linked to the quantity of humus and its qualitative state. Under natural soil formation conditions, the release of organic phosphorus and its sequestration follow natural cycles, whereas in agrocenoses, there is a predominance of humus depletion in organic phosphates and a disruption of seasonal cycles of expenditure and reproduction.

An important direction is the assessment of the impact of cultivation methods and fertilization on the reproduction of the sequestration capacity of C-CO_2 in humus and labile organic substances. It aims to identify the nature of sequestration enrichment of chernozem with organic phosphorus in agrocenoses, as well as to establish the patterns of P_{org} deposition in humus during the sequestration of C-CO_2 by agrocenoses in a seasonal cycle, which remains largely unexplored. Scientific sources analysis indicates that this aspect of the question has not been thoroughly investigated.

The goal of this study was to assess the influence of the C-CO_2 reserve in humus on soil formation and fertility of chernozem. To identify the reasons, rates, and existing limits of soil sequestration capacity reduction, the objective is to investigate the seasonal dynamics of carbon dioxide stocks in humus and labile organic matter, depending on cultivation methods and fertilization, in the agrocenosis of a short rotation crop rotation in the central part of the Forest-Steppe region of Ukraine.

MATERIALS AND METHODS

The research was conducted in the conditions of the central part of the left-bank Forest-Steppe of Ukraine in a long-term (over 35 years) stationary experiment at the Drabiv Research Field (coordinates 49°55'58.7"N 32°06'43.0"E) of the Cherkasy State Agricultural Research Station "National Scientific Center" Institute of Agriculture of the National Academy of Agrarian Sciences. The soil is chernozem typical *(Chernozems Chernic)* with low humus content, coarse-dusty light loamy, with a humus content of 3.8–4.2%, available phosphorus content of 120–140 mg per 1,000 g of soil, available potassium content of 80–100 mg per 1,000 g of soil, and pH in water of 6.8–7.0. The size of the sown area is 162 m^2, and the accounting area is 100 m^2.

The research was conducted during the period from 1976 to 2022 in a multifactorial stationary experiment. The experiment involved a 5-field crop rotation: perennial grasses - winter wheat - sugar beet - maize - barley + perennial grasses (cereals - up to 60%, technical crops – up to 20%; perennial grasses - up to 20%).

Fertilization system: 6.0 tons per hectare of by-products; $N_{31\text{-}62}P_{33\text{-}66}K_{41\text{-}82}$ per 1 hectare of crop rotation area, or NPK - Σ250–350 kg of active substances. Until 1999, 6 tons per hectare of manure were applied, and from 2000 to 2022 - 6–7 tons per hectare of by-products.

Primary tillage methods: variable-depth plowing (0.22–0.25 m) for all crops; chisel plowing (0.22–0.25 m) for all crops. Both experiments had three replications.

In laboratory conditions, soil samples were analyzed in triplicate. The content of humus was determined using the method developed by I.V. Tyurin, modified by V. M. Symakov (DSTU 4289:2004); labile organic matter was determined according to DSTU 4732:2007.

The content of organic phosphates (P_{org}) in humus was determined using the method developed by B.S. Nosko (Nosko et al., 2008; Nosko, 2018). It has been established that the correlation coefficient between the total humus content and P_{org} is $R = +0.98 \pm 0.02$, $R^2 = 0.96$ for the entire genetic zonal series of chernozems (podzolized - typical - ordinary - southern). The relationship is described by a straight line according to the equation: $Y = 15.5+17.2x - 1.47x^2$, where Y is the P_{org} content, mg 100 per g of soil, x is the humus content, %. Based on the established dependence between the total humus content and the content of LOS, the P_{org} content in labile organic matter was determined. Subsequently, the content of humus, LOS, and P_{org} were recalculated into reserves (t·ha^{-1}), which forms the basis for the presented study.

The synthesis of crop rotation productivity, soil moisture regime indicators, climatic parameters, and the calculation of research results were conducted using the 'Method of Dispersion Analysis' with the application of the 'STATISTICA-10' software. Non-parametric statistical methods, correlation analysis, factor analysis, and cluster analysis were employed in the study.

RESULTS

Changes in humus C-CO_2 reserve in chernozem during fallow are associated with the manifestation of natural cyclicality from spring to autumn, similar to the overall humus content (Demydenko, 2013; Tonkha et al., 2017). The C-CO_2 reserve in the 0–0.2 m layer of chernozem in April was 195 t ha^{-1}, and in the soil layer 0.2–0.3 m deep, it was 79 t ha^{-1}. The reserve in the 0–0.3 m layer was 275 t ha^{-1}. A decrease in the C-CO_2 reserve was recorded in July, amounting to –15 t ha^{-1}, –3 t ha^{-1}, and –18 t ha^{-1}, respectively, for the soil layers. In September, there was a reproduction of the C-CO_2 reserve, which increased by +27 t ha^{-1}, +12 t ha^{-1}, and +39 t ha^{-1}. The period from April to July is considered a consumptive one, while July to September is a restorative or sequestration period. In natural conditions, the sequestration period is more intensive compared to the reproductive one by 1.8 times, 4 times, and 2.2 times, respectively, for the soil layers 0–0.2 m, 0.2–0.3 m, and 0–0.3 m. Cyclically, with changes in the C-CO_2 reserve, the P_{org} reserve also changed. During the reproductive period, the expenditure of the P_{org} reserve in humus was –0.058 t ha^{-1} (0–0.2 m), –0.078 t ha^{-1} (0.2–0.3 m), and –0.136 t ha^{-1} (0–0.3 m), while the reproduction of the P_{org} reserve in the sequestration period was +0.146 t ha^{-1}, +0.145 t ha^{-1}, and +0.295 t ha^{-1}, which is 2.5, 1.85, and 2.17 times more intense than expenditures, respectively, for soil layers. The ratio of the C-CO_2 reserve to P_{org} for the periods was from 140:1 to 151:1 or 38–42:1 in terms of C_g, indicating the high stability of the C-CO_2 and C_g reserves to mineralization, ensuring the accumulation of P_{org} under the conditions of long-term fallow. The intensity of the reproduction of the C-CO_2 and P_{org} reserves in the presence of fallow and the positive balance contribute to the manifestation of high sequestration capacity of fallow (Fig. 1).

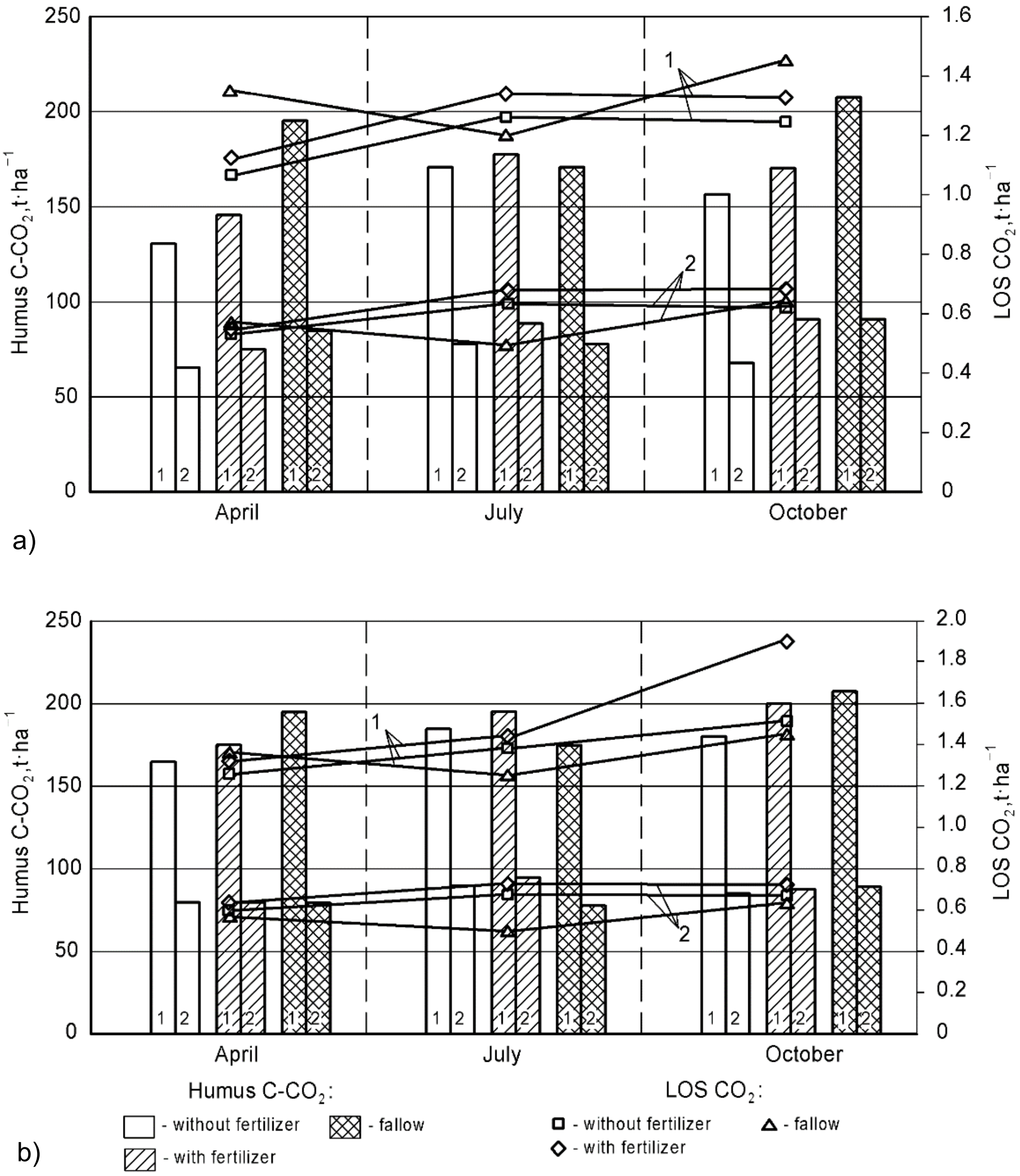

Figure 1. The seasonal dynamics of the C-CO_2 reserve in humus and labile organic substances (LOS) depend on the cultivation method and fertilization in the crop rotation chain of wheat-sugar beet-corn in the 45th year of the experiment: a – moldboard plowing; b – chisel plowing; 1 – 0–0.2 m; 2 – 0.2–0.3 m.

Systematic plowing leads to a change in the seasonal variation of C-CO_2 and P_{org} reserves. For example, in April, without fertilization, the C-CO_2 reserve in the 0–0.2 m layer was 1.5 times smaller, and in soil layers 0.2–0.3 m and 0–0.3 m, it was 1.3 and 1.4 times smaller, respectively, compared to fallow. Similarly, in July, the C-CO_2 reserve was 1.1 times smaller (0–0.2 m) and 1.2 times smaller (0–0.3 m) compared to fallow, which is –20 t ha^{-1} (0–0.2 m) and –15 t ha^{-1} (0–0.3 m). In September, the C-CO_2 reserve during plowing decreased and was 1.34 times smaller (0–0.2 m), 1.33 times smaller (0.2–0.3 m), and 1.35 times smaller (0–0.3 m) compared to fallow, or –102 t ha^{-1}, –22 t ha^{-1}, and –76 t ha^{-1}, respectively, for soil layers.

During chisel plowing without fertilization, the C-CO_2 reserve from April to September was higher compared to plowing by +40 t ha^{-1} (0–0.2 m), +90 t ha^{-1} (0.2–0.3 m), and +55 t ha^{-1} (0–0.3 m). In July, the reserve was higher by +25 t ha^{-1} (0–0.2 m), +13 t ha^{-1} (0.2–0.3 m), and +38 t ha^{-1} (0–0.3 m). In September, the C-CO_2 reserve was higher compared to plowing by +30 t ha^{-1} (0–0.2 m) and +54 t ha^{-1} (0–0.3 m). During chisel plowing, the C-CO_2 reserves per assessment period were closest to fallow. With the addition of fertilizers, the C-CO2 reserve in April increased by 15 t ha^{-1} in the 0–0.2 m layer and by 25 t ha^{-1}in the 0–0.3 m layer during chisel plowing. Similar growth in the C-CO_2 reserve occurred in July: +12 t ha^{-1}, +10 t ha^{-1}, and +22 t ha^{-1}, respectively, for soil layers in the depth of the chernozem. A similar increase in the C-CO_2 reserve occurred in September. The cyclic nature of the seasonal variation in the C-CO_2 reserve with fertilizer application had the established character, as observed in the control without fertilization but at a higher quantitative level.

During chisel plowing with fertilizer application, an increase in the C-CO_2 humus reserve was observed compared to the plot where no fertilizers were applied but was lower compared to conventional plowing. The growth in the C-CO_2 reserve during the period from April to July was: +21 t ha^{-1} (0–0.2 m), +15 t ha^{-1} (0.2–0.3 m), and +36 t ha^{-1} (0–0.3 m). With chisel plowing, the increase tended to be 1.52 times (0–0.2 m) and 1.25 times (0–0.3 m) higher, but at a lower quantitative level. The change in the C-CO_2 humus reserve during the period from July to September was insignificant, indicating a predominance of C-CO_2 sequestration processes in the summer-autumn period during chisel plowing.

However, the overall analysis of the expenditure and replenishment of the C-CO_2 humus reserve showed that in the presence of fallow, there is a depletion of the C-CO_2 humus reserve from April to July: –15 t ha^{-1} (0–0.2 m), –3 t ha^{-1} (0.2–0.3 m), and –18 t ha^{-1} (0–0.3 m). In the period from July to September, there is an enhancement of humus C-CO_2 sequestration and an increase in the carbon oxide reserve by +27 t ha^{-1}, +12 t ha^{-1}, and +39 t ha^{-1}, respectively, for the soil layers.

During plowing on the control plot without fertilizers, there was an increase in the humus C-CO_2 reserve during the period from April to July: +35 t ha^{-1} (0–0.2 m), +12 t ha^{-1} (0.2–0.3 m), and +47 t ha^{-1} (0–0.3 m). However, from July to September, a decrease was observed: –10 t ha^{-1}, –10 t ha^{-1}, and –20 t ha^{-1}. With the application of fertilizers, the increase in the C-CO_2 reserve was similar to the control plot without fertilizers, but the expenditure was 1.42 times less, 3.3 times less, and 5 times less, respectively.

During chisel plowing, the increase in the humus C-CO_2 reserve from April to July on the control plot without fertilizers was +21 t ha^{-1} (0–0.2 m), +15 t ha^{-1} (0.2–0.3 m), and +36 t ha^{-1} (0–0.3 m). With the application of fertilizers, there was a tendency for growth: +20 t ha^{-1}, +10 t ha^{-1}, and +30 t ha^{-1}. However, the expenditure on the control plot without fertilizers was significantly less compared to plowing: –3 t ha^{-1}, –6 t ha^{-1}, and –9 t ha^{-1}. Regarding the 0–0.3 m layer, the expenditure was 2.2 times less. With the application of fertilizers, the reduction in the humus C-CO_2 reserve showed a weak tendency to decrease compared to plowing.

Seasonal changes in the humus C-CO_2 LOS reserve with fallow land content had a cyclic nature similar to the changes in the C-CO_2 reserve of the total humus. Expenditure of the labile humus C-CO_2 reserve during the period April-July was: –3.7 t ha^{-1} (0–0.2 m), and –3.8 t ha^{-1} (0–0.3 m), while the reproduction of the labile humus C-CO_2 reserve from July to September was: +1.15 t ha^{-1}, +0.62 t ha^{-1}, and +0.71 t ha^{-1}, respectively, at different depths. The reserve of the labile humus C-CO_2 during plowing in April without fertilization compared to fallow land was 4.8 times less (0–0.2 m) and 4.1 times less (0–0.3 m). In July, it was 2.56 times, 1.99 times, and 2.38 times less, and in September, it was 2.3 times, 2.5 times, and 2.16 times less, respectively, at different soil depths. The seasonal cyclicality of LOS differed from fallow land in that there was an increase in LOS from spring to fall, which is associated with the seasonal activation of humus due to old, more stable reserves of humus C-CO_2 (Table 1).

Table 1. Seasonal dynamics of labile organic substance and organic phosphates depending on cultivation, fertilization, and the state of fallow

Depth, m	Moldboard plowing			Chisel plowing		
	April	July	September	April	July	September
	C-CO_2 LOS, t ha^{-1} without fertilization					
0–0.2	2.28	2.85	2.67	18.0	24.0	15.0
0–0.3	3.41	4.21	3.95	23.0	30.0	20.0
	NPK – Σ250–350 kg of active substance					
0–0.2	14.1	25.0	11.4	22.0	33.0	24.0
0–0.3	16.0	26.6	12.8	28.0	38.0	30.0
	P_{org} LOS, t ha^{-1} NPK – Σ250–350 kg of active substance					
0–0.2	0.052	0.026	0.029	0.130	0.180	0.110
0–0.3	0.071	0.037	0.044	0.180	0.230	0.151
	NPK – Σ250–350 kg of active substance					
0–0.2	0.111	0.191	0.150	0.160	0.250	0.170
0–0.3	0.126	0.236	0.195	0.211	0.291	0.222
	Fallow					
	April		July		September	
	C-CO_2 LOS, t ha^{-1}					
0–0.2	11.0		7.31		8.45	
0–0.3	13.8		9.76		11.66	
	P_{org} LOS, t ha^{-1}					
0–0.2	0.075		0.064		0.081	
0.2–0.3	0.021		0.019		0.025	
0.3	0.096		0.083		0.106	

When fertilizers were applied during plowing, the LOS reserve increased compared to the control without fertilizers. In April, it increased by 6.2 times (0–0.2 m), 1.76 times (0.2–0.3 m), and 4.7 times (0–0.3 m); in July, it increased by 8.8 times (0–0.2 m), 1.2 times (0.2–0.3 m), and 6.3 times (0–0.3 m); in September, it increased by 3.18 times (0–0.2 m), 4.8 times (0.2–0.3 m), and 3.44 times (0–0.3 m). However, the C-CO_2 LOS reserve with fertilizer application during plowing was significantly higher than fallow, by 1.16–1.28 times (April), 2.6–3.4 times (July), and 1.34–1.5 times (September). On the control plot without fertilizers, the LOS reserve in the 0–0.3 m layer was 2.43–4.83 times lower (April), 1.99–2.38 times lower (July), and 2.3–2.5 times lower (September).

During chisel plowing, the LOS reserve in April exceeded the reserve during plowing in the 0–0.3 m layer by 4.34–7.67 times (without fertilizers) and 1.5–2.76 times (with fertilizers); in July - by 4.59–8.90 times (without fertilizers) and 1.32–3.16 times (with fertilizers); in September - by 4.52–4.04 times (without fertilizers) and 1.11–1.93 times (with fertilizers). The $C\text{-}CO_2$ LOS reserve, compared to fallow, during chisel plowing without fertilizers in April, July, and September was higher by 1.59–1.78 times, 2.31–3.29 times, and 1.4–1.78 times, respectively. With the application of fertilizers, it was higher by 1.99–2.0, 1.86–4.50, and 1.7–2.6 times, respectively, for each season.

Table 2. The seasonal dynamics of the ratio of $C\text{-}CO_2$ and labile organic substances (LOS) to P_{org} under different tillage and fertilization

Depth, m	Moldboard plowing			Chisel plowing		
	April	July	September	April	July	September
	$C\text{-}CO_2$ LOS to P_{org} without fertilization					
0–0.2	61 to 1	130 to 1	125 to 1	137 to 1	140 to 1	136 to 1
0–0.3	58 to 1	133 to 1	110 to 1	133 to 1	136 to 1	134 to 1
	NPK – Σ250–350 kg of active substance					
0–0.2	127 to 1	132 to 1	95 to 1	147 to 1	132 to 1	133 to 1
0–0.3	130 to 1	85 to 1	116 to 1	131 to 1	140 to 1	134 to 1
	humus $C\text{-}CO_2$ to P_{org} without fertilization					
0–0.2	121 to 1	130 to 1	124 to 1	134 to 1	135 to 1	132 to 1
0–0.3	121 to 1	126 to 1	117 to 1	134 to 1	134 to 1	133 to 1
	NPK – Σ250–350 kg of active substance					
0–0.2	130 to 1	133 to 1	128 to 1	136 to 1	135 to 1	132 to 1
0–0.3	134 to 1	133 to 1	131 to 1	134 to 1	134 to 1	133 to 1
	Fallow					
	April		July		September	
	$C\text{-}CO_2$ LOS to P_{org}					
0–0.2	149 to 1		115 to 1		120 to 1	
0–0.3	144 to 1		122 to 1		130 to 1	
	humus $C\text{-}CO_2$ to P_{org}					
0–0.2	147 to 1		142 to 1		147 to 1	
0–0.3	144 to 1		150 to 1		144 to 1	

Unlike the biochemistry of $C\text{-}CO_2$, where the gaseous form of the compound is an obligatory link in biospheric flows, phosphorus (P) biochemistry is associated with living organic matter (Nosko, 2017; Nosko, 2018). In other words, organic phosphorus is a bioavailable element, and its content in chernozem soils depends on the stock of organic matter ($C\text{-}CO_2$) of humus and the labile form of humus. The correlation coefficient between the content of organic phosphorus and humus, according to B.S. Nosko's calculations (Nosko et al., 2008), is $R = +0.994$ ($R^2 = 0.98$), and the relationship is expressed by a straight line.

On fallow land, the seasonal dynamics of the C-CO_2 LOS stock follows the seasonal dynamics of $P_{org(LOS)}$. A direct strong correlation has been established at the level of $R = +0.89 \pm 0.02$; $R^2 = 79$. During the period from April to July, a decrease in the $P_{org(LOS)}$ stock was observed in the 0–0.2 m layer by 1.15 times, and in the 0–0.3 m layer by 1.1 times. From summer to fall, the $P_{org(LOS)}$ stock was restored, and the stock in the 0–0.3 m layer increased by 1.1 times. The assessment of the ratio of the C-CO_2 LOS stock to the $P_{org(LOS)}$ stock showed that in the spring, a wide ratio of 138–149 to 1 was formed, indicating the 'conservation' of organic phosphates. In the summer, the ratio expanded to 115–128 to 1 (31–35 to 1), which is associated with the release of $P_{org(LOS)}$ due to the mineralization of humus LOS. In the fall, with the reproduction of the C-CO_2 LOS stock, $P_{org(LOS)}$ become more conservative and accumulate in humus. The positivity of the P_{org} stock relative to the resource-consuming period indicates an expanded reproduction of $P_{org(LOS)}$ as the C-CO_2 LOS stock itself (Table 2).

With systematic plowing without fertilizers, a cyclic pattern of $P_{org(LOS)}$ was identified, similar to the pattern on fallow land but at a lower quantitative level. In April, on the control plot without fertilizers, the $P_{org(LOS)}$ stock was smaller compared to fallow land by 1.69–1.85 times, and with the addition of fertilizers in the 0–0.3 m layer, it was larger by 1.29 times. In the soil layer, on the contrary, it was smaller by 6 times compared to fallow land.

In July, the pattern was similar. On the control plot without fertilizers, the $P_{org(LOS)}$ stock was smaller by 2.1–2.5 times, and with the addition of fertilizers, it was larger by 2–3 times compared to fallow land. In September, without fertilizers, the $P_{org(LOS)}$ stock with plowing without fertilizers was smaller by 1.5–2.4 times, and with the addition of fertilizers, it was larger by 1.70–1.96 times compared to fallow land. The ratio of the C-CO_2 LOS stock to $P_{org(LOS)}$ on the control plot without fertilizers was wide: 58–70 to 1 in April, 130–136 to 1 in July, and 85–125 to 1 in September, indicating high rates of mineralization and release of $P_{org(LOS)}$. With the addition of fertilizers, the C-CO_2 LOS stocks increased by 6.2 times (0–0.2 m) and 4.7 times (0–0.3 m) in April. In July, it increased by 8.8 times and 6.4 times, and in September, by 3.1 and 3.54 times, respectively, for soil layers. At the same time, the ratio of the C-CO_2 LOS stock to $P_{org(LOS)}$ on the fertilized background was broader: 127–132 to 1 in April, 38–132 to 1 in July, and 95–136 to 1 in September, indicating a more restrained mineralization of LOS and release of $P_{org(LOS)}$ compared to the control plot without fertilizers. With the addition of fertilizers in September, the $P_{org(LOS)}$ stock with plowing showed a stable tendency to increase in the soil layers of 0–0.2 m, 0.2–0.3 m, and 0–0.3 m, but the organic phosphorus stock did not reach the level observed in April.

During chisel plowing, an increase in the P_{org} stock was observed, which exceeded the increase during conventional plowing: in the soil layer 0–0.2 m – by 3.7 times; in the 0.2–0.3 m layer - by 2.7 times, and in the 0–0.3 m soil layer - by 3.4 times. With the addition of fertilizers, the $P_{org(LOS)}$ stock increased by 5 times (0–0.2 m); by 3 times (0.2–0.3 m); by 4.3 times (0–0.3 m).

During chisel plowing, the $P_{org(LOS)}$ stock was higher compared to conventional plowing by 1.13–1.16 times. With the addition of fertilizers, the Porg stock in September exceeded the stock in April by 1.10–1.55 times, but enrichment was higher during chisel plowing. The $P_{org(LOS)}$ stock relative to the control without fertilizers during plowing in April was higher by 2.1–3.2 times, in July - 4.7–7.8 times, and in September - 2.3–3.7 times. With the addition of fertilizers, the $P_{org(LOS)}$ stock in April increased by 1.27 times

(0–0.2 m) and by 1.16 times (0–0.3 m). In July, the $P_{org(LOS)}$ stock increased by 1.45 times and 1.30 times, and in September - by 1.5 times and 1.44 times, respectively, for soil layers. Compared to fallow, the $P_{org(LOS)}$ stock during chisel plowing for the determination periods was higher by 2.1–2.4 times in April, 1.61–3.90 times in July, and 1.78–2.36 times in September.

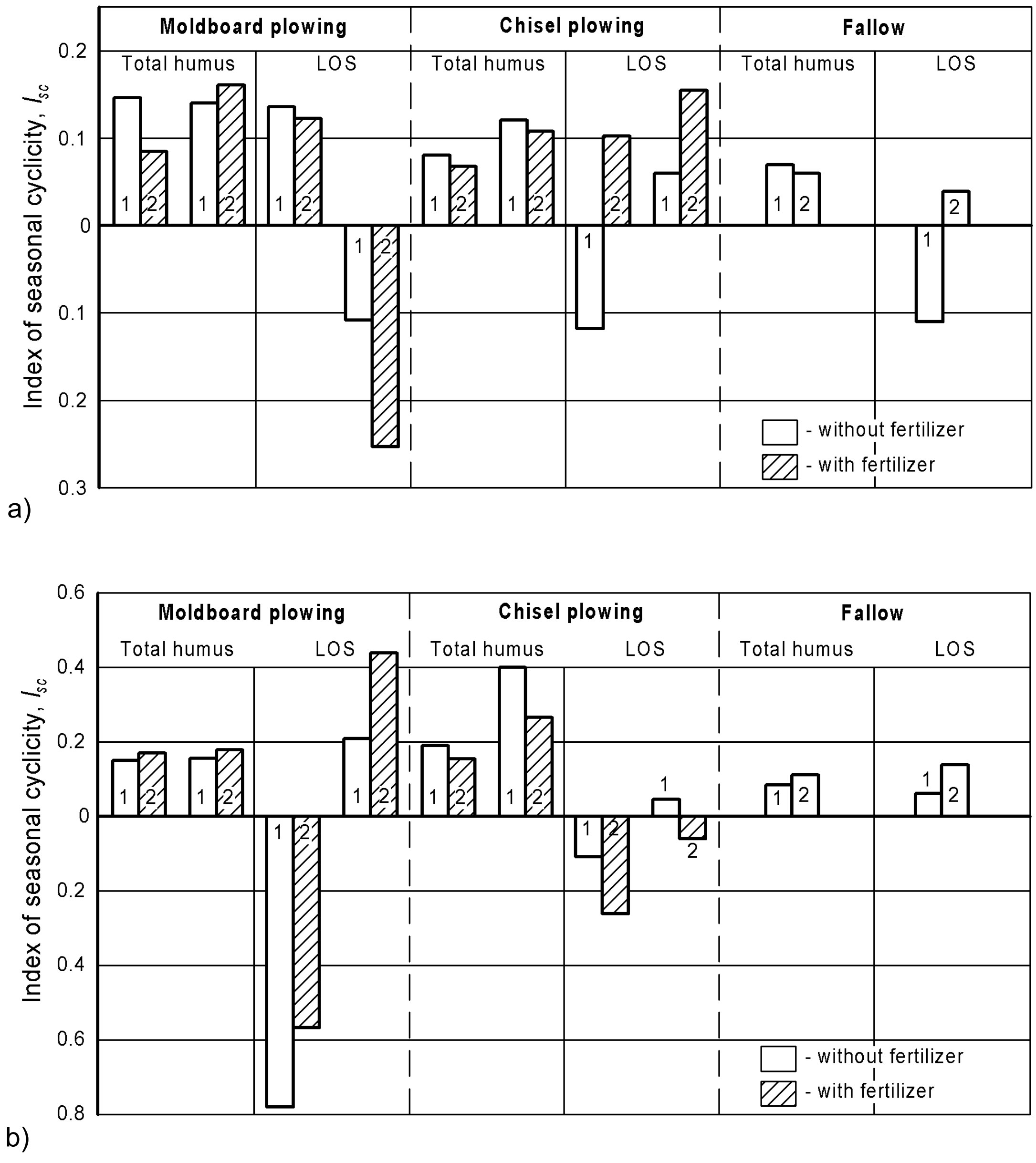

Figure 2. The change in the Seasonal Cyclicity Index (I_{sc}) depending on fertilization and cultivation method: a – humus C-CO_2 and LOS; b – organic phosphates P_{org}; 1 – 0–0.2 m; 2 – 0–0.3 m.

The ratio of the C-CO_2 LOS stock to $P_{org(LOS)}$ in the 0–0.3 m soil layer in April was 115–147 to 1, in July it was 132–147 to 1, and in September it was 1.31–1.34 to 1. The wider ratio of C-CO_2 LOS to $P_{org(LOS)}$ during chisel plowing compared to conventional plowing with the addition of fertilizers indicates lower mineralization of C-CO_2 LOS and the release of $P_{org(LOS)}$.

To determine the Seasonal Cyclicity Index (I_{sc}) of humus state parameters, we propose conducting calculations using the following expression:

$I_{sc} = \Delta_k / Q_{min}$, where I_{sc} – Seasonal Cyclicity Index; Δ_k – is the difference between the final (Lk-autumn) value of the parameter and the initial (Lp-spring) value; Q_{min} – is the minimum value of the parameter (summer).

It has been determined that on fallow land, the Isc of the humus C-CO_2 stock in soil layers of 0–0.2 m and 0–0.3 m was: I_{sc} = 0.06–0.07, while with plowing without fertilizer application, I_{sc} increased by 2.15 times, and with chisel plowing, it approached the value when fallow. With fertilizer application, I_{sc} increased by 2.0–2.7 times for both plowing methods, and 1.74–1.80 times, respectively. The Seasonal Cyclicity Index of the C-CO_2 LOS content when fallow in the soil layer of 0–0.2 m acquired a negative value, while in the 0–0.3 m soil layer, I_{sc} = 0.039 (Fig. 2).

With plowing without fertilizer application, I_{sc} acquired a positive value, while with fertilizer application, I_{sc} values were negative: I_{sc} = –0.108 to –0.25. With chisel plowing without fertilizer application in the 0–0.2 m soil layer, I_{sc} was at the fallow level (I_{sc} = –0.117), while in the 0–0.3 m layer, it reached I_{sc} values of 0.10. With fertilizer application in chisel plowing, I_{sc} had a positive value in the 0–0.2 m and 0–0.3 m layers: I_{sc} = 0.06 and I_{sc} = 0.16, respectively. In contrast, with plowing, I_{sc} values were negative, indicating a disruption of the seasonal cyclicity. With chisel plowing, the I_{sc} process is restored towards cyclicity when fallow.

The trends in changes in humus and LOS carbon stocks indicate that in the moldboard plowing-chisel plowing-fallow sequence, I_{sc} during chisel plowing is closer in value to the seasonal cyclicity of fallow than the seasonal cyclicity during plowing. This suggests the restoration of I_{sc} in the latter case.

The index of seasonal cyclicity (I_{sc}) of the humus I_{sc} stock, when fallow is present in the 0–0.3 m soil layer, was I_{sc} = –0.083 to –0.11. However, during plowing without fertilizer application, I_{sc} was higher by a factor of 1.75, and during chisel plowing, it was higher by a factor of 2.24 in the 0–0.2 m soil layer, reaching fallow levels. With fertilizer application during plowing, I_{sc} in the 0–0.3 m soil layer increased by 1.63–1.85 times compared to fallow, and during chisel plowing in the 0–0.2 m soil layer, it was higher by a factor of 5 compared to fallow and by a factor of 2.6 compared to plowing. In the 0–0.3 m soil layer, I_{sc} during chisel plowing increased by 2.4 times compared to fallow and by 1.44 times compared to plowing.

The index of seasonal cyclicity (I_{sc}) of the $P_{org(LOS)}$ over fallow in the 0–0.2 m and 0–0.3 m soil layers was I_{sc} = 0.065–0.14. In contrast, during plowing without fertilizers, I_{sc} = –0.58 to –0.79, and during chisel plowing, I_{sc} = –0.11 to –0.27. With fertilizer application, I_{sc} increased by 3.10–3.15 times compared to fallow, and during chisel plowing, I_{sc} values approached those for fallow.

The trends in $P_{org(LOS)}$ storage changes indicate that, in the sequence of moldboard plowing-chisel plowing-fallow, chisel plowing tends to align its seasonal cyclicity with fallow. The general pattern of seasonal cyclicity for all humus state parameters suggests that a decrease in I_{sc} values, whether during fallow or chisel plowing, indicates stabilization of I_{sc}, while an increase in the cyclicity index is associated with disruption, as observed during plowing.

DISCUSSION

Seasonal cyclicality of humus is based on the concept of biochemical cycles (Ponomareva et al., 1975), which proposed three levels, one of which is the biochemical cycle at the level of soil microbiological populations. Furthermore, there is a biogeochemical cycle at the level of the lowest soil invertebrates and the cycle of forest and grassland biogeocenoses. Expanding the concept of biogeochemical cycles, V.V. Ponomareva defined a list of mandatory parameters for their study, namely: biomass, annual increment, life-metabolites, and organic matter of the soil; the stability of biogeochemical cycles is based on the concept of biotic self-regulation of soil processes in the transformation of organic matter in natural ecosystems (Shilova, 1988).

The direction and speed of transformation (sequestration) of organic matter into humus, which enters chernozem, is linked to the activities of soil heterotrophic microorganisms. This is because these soil biota are biologically involved in the transformation of organic compounds. The sequestration of C-CO_2 in humus begins with the active activity of the heterotrophic microbial pool, which acts as a connecting link between C-CO_2 from the atmosphere, soil air, and the humus reserve of chernozem. The direction of C-CO_2 sequestration in humus in annual and seasonal cycles is determined by the interaction of agricultural crops, the successive interaction of plants and microorganisms, their combined physiological activity and life processes. However, the determining factor is the interaction of the soil heterotrophic microflora in the root zone, the root system, and the aboveground part of agricultural crops (Shykula et al., 2020; Shykula & Makarchuk, 2020).

The nature of interaction depends on the chernozem tillage: systematic plowing disrupts the natural mechanism of interaction in the system of microorganisms in the root zone-root system-aboveground part of plants, while systematic chisel plowing stimulates and directs the development of chernozem towards natural cenoses, changing (reproducing the seasonal sequestration cycle) primarily the soil conditions for the life activities of trophic components of the agrocenosis (Shykula & Demydenko, 1998; Shykula, 2001). Systematic chisel plowing of chernozem in agrocenoses, against the background of optimal application of organic and mineral fertilizers, contributes to the formation of stable trophic groups of heterotrophic microorganisms with a clearly defined spatial attachment to the 0–0.15 m soil layer. This ensures the reproduction of their ecologically balanced seasonal dynamics and improves the humus condition of chernozem (Shykula, 2001).

During chisel plowing, the maximum values of root exudation occur when the content of C-CO_2 in the soil is minimal in the seasonal cycle, initiating the process of heterotrophic fixation (sequestration) of C-CO_2 by soil microflora. Carbon from soil air and soil (CO_2 in soil solution) is assimilated (sequestered) by heterotrophic microbes, leading to the formation of new organic substances. These substances are present in their protoplasm, and during microbial autolysis (shell breakdown), they are released into the soil solution as freshly formed protohumic substances. These substances interact with the soil complex, releasing nitrogen-containing radicals of humic acids, which are part of fulvates. After their condensation, they replenish the C-CO_2 of stable humates, accompanied by an increase in ATP content in the soil by 25–250% during chisel plowing. This is logically associated with the activity of heterotrophic saprophytic microorganisms.

The organic secretions resulting from the autolysis of the protoplasm of heterotrophic microbes contain amino acids, amines, amides, and protohumic fragments. These substances, based on the principle of complementarity, can be immediately involved in the reproduction process of organic matter in chernozem, thereby enhancing the seasonal sequestration of C-CO_2.

Soil microorganisms are the most active and versatile heterotrophic agents in agro- and natural ecosystems. As a result of their activity, 2/3 of all CO_2 in the soil air is formed, with 1/3 originating from the activity of the root system (Miltner et al., 2005). Through the root system, up to 20% of the total carbon mass (C-CO_2) of root exudates and fine roots is released into the soil, replenishing the soil environment with CO_2 through mineralization. The proportion of root-derived CO_2 from the total varies from 10 to 40% (Burdina et al., 2016; Yermakov et al., 2021). It is likely that not the entire volume of root exudates is sequestered into the soil humus, and a significant part is consumed by the saprophytic heterotrophic microflora, for which such a substrate is more physiologically active (Šantrůčková et al., 2005; Burdina & Priss, 2016). Systematic chisel plowing of the soil in crop rotation stimulates the reproduction of the seasonal mechanism of C-CO_2 sequestration due to more optimal moisture conditions and an increase in the biogenicity of soil conditions, providing a water-soluble state of protohumic and humic substances at the moment of their formation. This leads to deep saturation of the chernozem layer with the solution of humic acids and freshly formed protohumic substances and $Ca(HCO_3)_2$ (WMO Greenhouse Gas Bulletin, 2012).

Carbon sequestration during systematic chisel plowing and fertilization involves the activation of atmospheric carbon dioxide intake by the living organic matter of agricultural crops (photosynthesis), with subsequent transformation of by-products, harvested and root residues, and root exudate which is formed in C-CO_2 humus with an enhancement of humification coefficients by 10–20% for by-products and root exudates as an active form of compost. During chisel plowing, organic matter not only enters the soil but is also stabilized by optimizing humification-mineralization processes. Therefore, it is protected from rapid decomposition but is still capable of slow mineralization to achieve a sufficient level of effective fertility. Soil carbon sequestration can be assessed by changes in the total organic carbon (C_{org}) content in chernozem from July to September, where the storage of C-CO_2 in humus and labile humic substances during chisel plowing increases compared to conventional plowing, aiming to reproduce the reserves found in natural fallow conditions.

Soil carbon sequestration during chisel plowing enhances the absorption of CO_2 from the atmosphere by generating additional crop biomass. Therefore, deposition is aimed at preserving C_{org} in chernozem and preventing its rapid return from the soil to the atmosphere during mineralization. The ability of chernozem to saturate with organic carbon has a limit, beyond which accumulation is not possible (Dynarski et al., 2020). This limit should be considered based on the chernozem content in the fallow state. The sequestration of organic matter is determined by both its specific internal properties and external physicochemical, biological, and agroecological conditions that limit the rate of organic matter decomposition, thereby ensuring its stability.

The level of organic matter content in the chernozem agroecosystem depends on the combination of factors such as the yield of the pure agricultural production, the quality of plant residues, hydrothermal conditions, topography, mineralogical and granulometric composition, chemical and biological properties of chernozem, agricultural practices (cultivation and fertilization), and the presence of disruptive influences that initiate carbon losses. As a result, under chisel plowing in short rotation crop rotations, systematic use recreates spatial, seasonal, and multi-year variability in the organic matter content, similar to the content in virgin chernozem.

CONCLUSIONS

1. Under fallow, the seasonal dynamics of the $C\text{-}CO_2$ humus and LOS reserves follow the seasonal dynamics of $P_{org(LOS)}$ with a strong correlation at the level of $R = +0.89 \pm 0.02$; $R^2 = 79$. During the period from April to July, there is a reduction in the $P_{org(LOS)}$ reserve in the 0–0.2 m layer by 1.15 times, and in the 0–0.3 m layer by 1.1 times. From summer to autumn, the $P_{org(LOS)}$ reserve is restored, and the $P_{org(LOS)}$ reserve in the 0–0.3 m layer increases by 1.1 times.

2. Under chisel plowing and fertilization, the increase in the $C\text{-}CO_2$ reserve during the April–July period was +21 t ha^{-1} (0–0.2 m) and +36 t ha^{-1}a (0–0.3 m). In the case of plowing, there was a tendency for an increase by 1.52 times (0–0.2 m) and 1.25 times (0–0.3 m) during the same period, but it occurred at a lower quantitative level. During the July–September period, the change in the $C\text{-}CO_2$ humus reserve was insignificant, indicating the predominance of $C\text{-}CO_2$ sequestration processes in the summer-autumn period.

3. Under chisel plowing, the LOS reserve in April exceeded the reserve under plowing in the 0–0.3 m layer by 4.34–7.67 times (without fertilizers), 1.5–2.76 times (with fertilizers); in July, it exceeded by 4.59–8.90 times (without fertilizers) and 1.32–3.16 times (with fertilizers); in September, it exceeded by 4.52–4.04 times (without fertilizers) and 1.11–1.93 times (with fertilizers). The $C\text{-}CO_2$ LOS reserve under fallow, compared to chisel plowing without fertilizers, was higher by 1.59–1.78 times in April, 2.31–3.29 times in July, and 1.4–1.78 times in September. With fertilization, the increase was 1.99–2.00, 1.86–4.50, and 1.7–2.6 times, respectively, for the corresponding seasons.

4. Trends in the changes of $C\text{-}CO_2$ and LOS reserves indicate that in the plowing-chiseling-fallow sequence, the cyclic index decreases with chiseling approaching the seasonal cycle of fallow, compared to the seasonal cycle with plowing. However, the trends in $P_{org(LOS)}$ reserves suggest that in the plowing-chiseling-fallow sequence, the chisel plowing also aligns its seasonal cycle with that of fallow. The general regularity of seasonal cyclicality for all humus state parameters lies in the fact that the decrease in I_{sc} values, whether on fallow or with chisel plowing, indicates the restoration of I_{sc}. In contrast, the increase in the cyclic index tends towards the disruption of the natural order, as observed with plowing.

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