GEOECOLOGY

Monitoring of Organic Carbon Content in Soils of Agroecosystems of the Central Chernozem Region

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Abstract—The research was conducted in 2010−2022 in Belgorod oblast, which is part of the Central Chernozem Economic Region and located on the southwestern and southern slopes of the Central Russian Upland. The aim of the research was to analyze the results of the monitoring of the organic carbon content in the soils of agroecosystems under conditions of large-scale biologization of agriculture. The study found that the typical and leached chernozems lost 40.0−42.0% of organic carbon during long-term use in agriculture compared to their counterparts in natural ecosystems. On average, for the studied subtypes of slightly washed-out chernozems, the decrease in the content of this parameter was 14.5−16.4% compared to unwashed arable soils. The organic carbon content was 1.87−2.22 and 5.30−6.98 times lower in the genetic B horizon and the upper layer of the C horizon, respectively, than in the plow horizon. As a result of the implementation of comprehensive measures aimed at increasing the supply of organic matter to the soil and reducing its losses, the weighted average C_{org} content in the arable soils of the region increased by 0.174%, which corresponds to the accumulation of 19.1 carbon units/ha. A direct linear relationship has been established between the levels of organic carbon and easily hydrolyzable nitrogen in soils.

INTRODUCTION

Soils play an important role in the carbon exchange between terrestrial ecosystems and the atmosphere, since they are both sources and sinks of greenhouse gases [1]. Long-term agricultural use of soils was accompanied by a 25−75% decrease in their organic carbon content compared to virgin counterparts in natural ecosystems [2]. This is one of the main parameters used to assess the agroecological condition of land types [3]. Restoring the lost stocks of organic carbon in the soils of agroecosystems is a priority task of today. Its successful accomplishment will improve soil fertility and crop yield, as well as reduce carbon dioxide emissions into the atmosphere [4, 5]. However, for many years, there has been no actual experience in coping with this task on a scale of a Russian Federation subject.

Since 2011, the Government of Belgorod oblast has been implementing a concept of agrotechnology biologization, which is a constituent part of the course for the ecologization of the entire agroindustrial complex [6, 7]. One of the tasks was to maximize the carbon sequestration through plant biomass conversion, subsequent incorporation into the soil and transformation into soil organic matter with a decomposition period of 10−100 years. In modern scientific literature, the concepts of carbon sequestration and carbon deposition in soil are differentiated. Carbon deposition refers to its long-term (over 100 years) storage as part of soil humus. Soil carbon sequestration implies the accumulation of atmospheric carbon dioxide by new plant biomass, while deposition aims at preventing the rapid return of organic carbon from soil to the atmosphere [2].

The purpose of this work is to summarize and analyze the results of the monitoring of organic carbon content in the soils of agroecosystems in Belgorod oblast under conditions of large-scale agriculture biologization.

METHODS

The research was conducted in 2010−2022 in Belgorod oblast, which is part of the Central Chernozem Economic Region and is located on the southwestern and southern slopes of the Central Russian Upland.
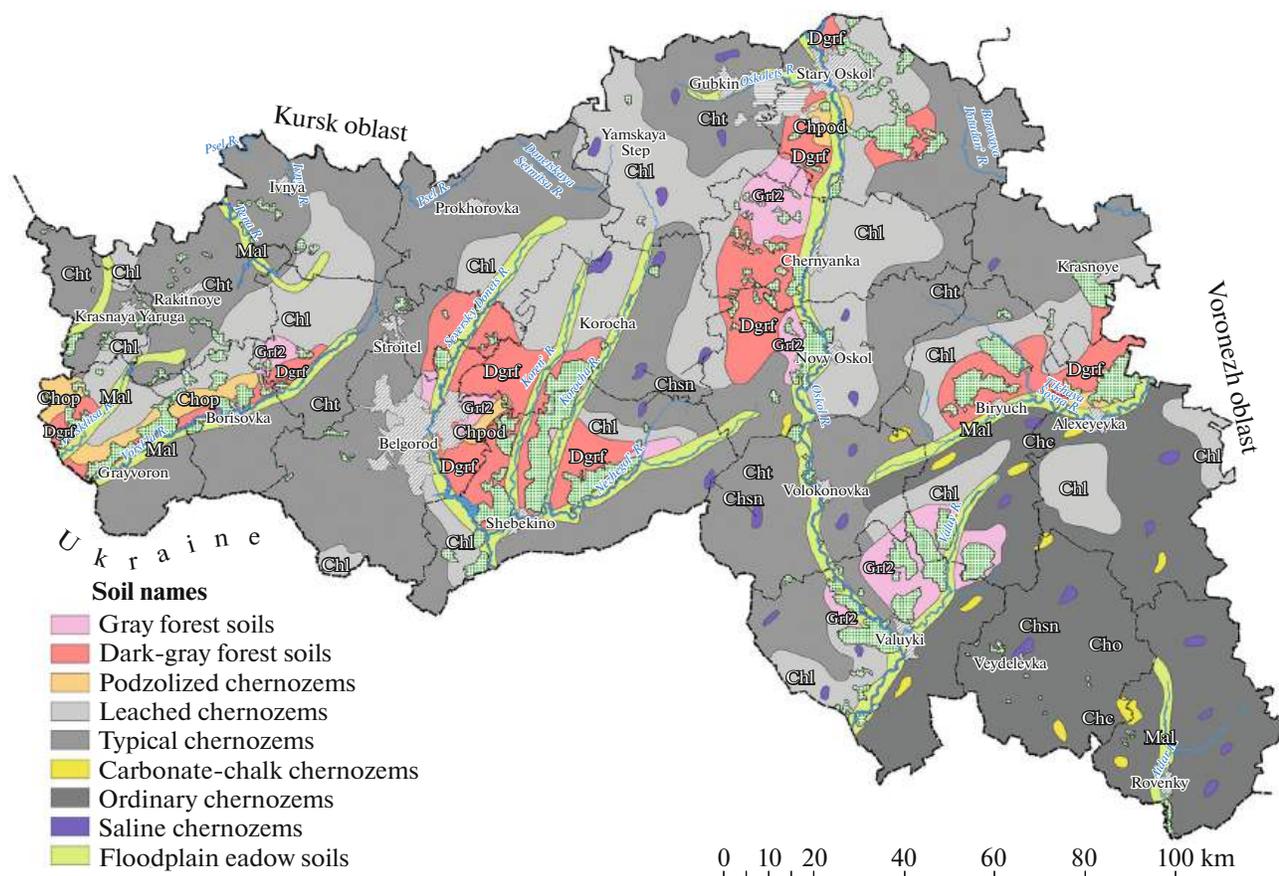
Fig. 1. Soil map of Belgorod oblast.

This area comprises forest-steppe and steppe natural zones. The arable soils of the forest-steppe zone are dominated by typical chernozems (44.8% of all arable soils in the region) and leached chernozems (25.7%), while in the steppe zone, by ordinary chernozems (13.0%). The proportion of the eroded arable soils is 47.9% [8, 9]. The eroded soils are dominated by slightly washed-out chernozems, where the A horizon is washed out by up to 30% [10].

The area sown under all agricultural plants in 2019−2022 was 1440400 ha on average. The structure of the sown areas is dominated by winter wheat (27.6%), soybeans (19.6%), sunflower (11.5%), grain maize (8.6%), and barley (7.5%) [11].

The influence of soil exposure and degree of erosion on organic carbon content, as well as the patterns of intra-profile distribution of this parameter was studied within the framework of a soil erosion survey. The soil profiles were constructed within the perimeter of the Gubkinsky urban district and the Prokhorovsky municipal district in the forest-steppe zone and within the Rovensky municipal district in the steppe zone. The background monitoring was conducted at the Yamskaya Steppe watershed site within the Belogorie State Natural Reserve, located in the Gubkinsky urban district (Fig. 1).

In this work we used the materials from the 9th (2010−2014), 10th (2015−2018), and 11th (2019−2022) cycles of comprehensive agrochemical survey of arable soils. Samples were taken from elementary plots up to 20 ha in area from the arable (0−25 cm) soil layer; organic carbon content (C_{org}) was determined by the common Tyurin method used in agrochemical service [1]. The content of easily hydrolyzable (alkali-hydrolyzable) nitrogen was estimated by the Kornfeld method [12]. The average content of physical clay (particles <0.01 mm) was 56.2% in leached chernozems, 57.8% in typical chernozems, and 70.5% in ordinary chernozems. All analyses were performed at the accredited testing laboratory of the Federal State Budgetary Institution Center of Agrochemical Service "Belgorodsky."

To establish the relationship between the contents of organic carbon and easily hydrolyzable nitrogen, we created a dataset of 100 soil samples from the forest-steppe zone and 100 soil samples from the steppe zone based on the results of the agrochemical survey in 2019−2022.
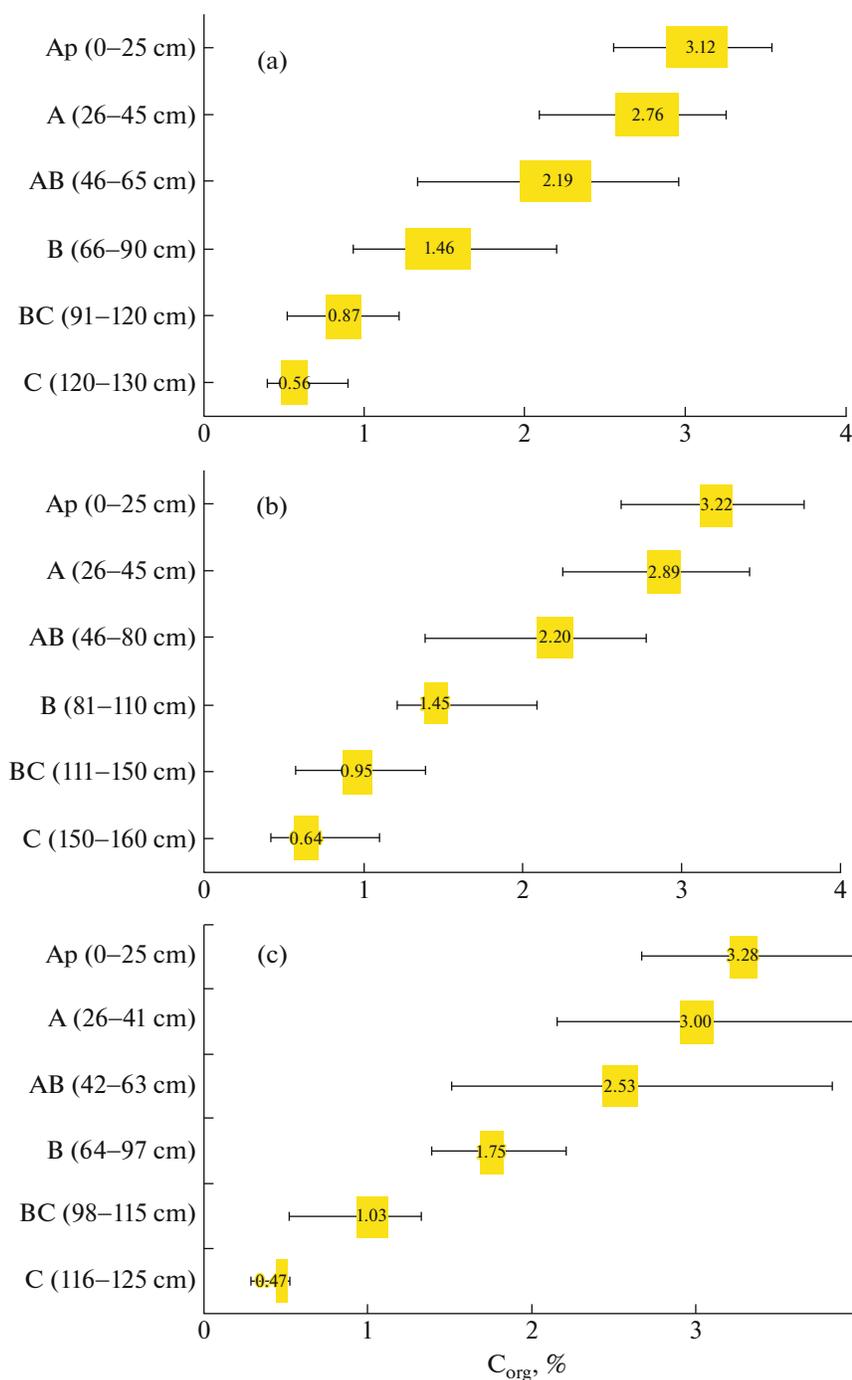
Fig. 2. Distribution of organic carbon content along the profile of (a) leached, (b) typical, and (c) ordinary chernozems, %.

Statistical processing of the soil-erosion survey data was conducted using the GIS "Agroecologist Online" software package and included the calculation of a confidence interval for mean values ($\bar{x} \pm t_{05}s\bar{x}$) and a coefficient of variation (V, %) [13−15].

Nearly 70000 samples were processed for C_{org} content in each cycle of the comprehensive agrochemical survey, and a weighted average value of this parameter was calculated for the soils in the region. During the variational-statistical analysis of such a large sample, the weighted mean error was less than 0.0001%. When recalculating C_{org} content to its stocks, the mass of the plow horizon was taken equal to 3000 t/ha (the volume of 2500 m³; the bulk density of 1.2 t/m³). The C_{org} content cartograms were created using the GIS "Agroecologist Online."

Table 1. Organic carbon content in the 0−25 cm layer of chernozems

A degree of erosion	Exposure	$\overline{x} \pm t_{05}s\overline{x}$	lim	V, %	n
Leached chernozem					
Unwashed	Flat interfluve	3.40 ± 0.06	3.02−3.94	7.0	63
Slightly washed-out	Western, eastern	2.90 ± 0.24	2.15−3.54	14.1	14
Slightly washed-out	Southern	2.78 ± 0.13	2.09−3.31	10.2	22
Slightly washed-out	Northern	2.93 ± 0.16	2.03−3.65	13.3	26
Typical chernozem					
Unwashed	Flat interfluve	3.38 ± 0.05	3.02−3.89	5.9	63
Slightly washed-out	Western, eastern	2.88 ± 0.18	2.15−3.48	12.1	17
Slightly washed-out	Southern	2.80 ± 0.14	1.57−3.42	14.4	36
Slightly washed-out	Northern	2.98 ± 0.09	1.97−3.65	11.1	52
Ordinary chernozem					
Unwashed	Flat interfluve	3.36 ± 0.08	3.02−4.00	7.5	30
Slightly washed-out	Western, eastern	2.81 ± 0.10	2.44−3.13	7.9	20
Slightly washed-out	Southern	2.74 ± 0.12	1.91−3.13	11.3	30
Slightly washed-out	Northern	2.88 ± 0.07	2.38−3.19	6.9	30

RESULTS AND DISCUSSION

The chernozem soils of Belgorod oblast formed under herbaceous vegetation in the post-glacial period (9000−12 000 years ago). In the soils of natural ecosystems, the level of C_{org} content depends on the features of the soil-forming process. In the humus-accumulative horizon of background (not used in agriculture) leached chernozems and typical chernozems, the C_{org} content is 5.63 and 5.86%, respectively. The period of intensive use of virgin soils in agriculture began ~250−300 years ago [16]. Since then, the C_{org} content in the plow horizon of unwashed leached and typical chernozems has decreased by 40−42% relative to the background soils, down to the level of 3.38−3.40% [17]. According to some estimates, C_{org} losses in the chernozems of the Central Chernozem region may reach nearly 50% of the original content in arable soils [16].

In the forest-steppe zone, depending on slope exposure, slightly washed-out leached and typical chernozems contain 2.78−2.98% of C_{org}, while in the steppe zone, slightly washed-out ordinary chernozems contain 2.74−2.88% of C_{org}. No significant differences in this parameter were found between the different subtypes of chernozems in the forest-steppe and steppe zones. On average, for all subtypes of slightly washed-out chernozems, the loss of C_{org} is 14.5−16.4% compared to unwashed counterparts. The soils on the northern (cold) slopes tend to have higher C_{org} content than on the western and eastern (neutral) slopes, and especially on the southern (warm) ones. This is explained by the more intense development of erosion processes during spring snowmelt, which is more intense on southern slopes than on northern and neutral ones (Table 1). This pattern is typical of the entire Central Chernozem region [18].

Along the depth of the chernozem soil profile, the C_{org} content consistently decreases [15]. In our studies, the average value of this parameter in the lower part of the humus-accumulative horizon (A) of the studied subtypes of chernozem was 1.08−1.13 times lower than in the plow horizon (A_p). In the genetic AB and B horizons, the C_{org} content was 1.30−1.46 and 1.87−2.22 times lower, respectively, than in the A_p horizon. In the BC horizons and in the upper layer of the parent rock (C), the organic carbon content was 3.18−3.59 and 5.30−6.98 times lower, respectively, than in the plow horizon (Fig. 2).

Based on the results of the comprehensive agrochemical monitoring, we established that the weighted average C_{org} content in the arable soils of the region increased by 0.174% (from 2.900 to 3.074%) in the 11th cycle compared to the 9th one. This corresponds to the increase in C_{org} stocks in the plow horizon by 5.22 t/ha, which is equivalent to the accumulation of 19.1 carbon units/ha (19.1 t CO_2) [17]. Such a pattern is absent in other regions of the Central Chernozem region and is typical only of Belgorod oblast [8, 17, 20].
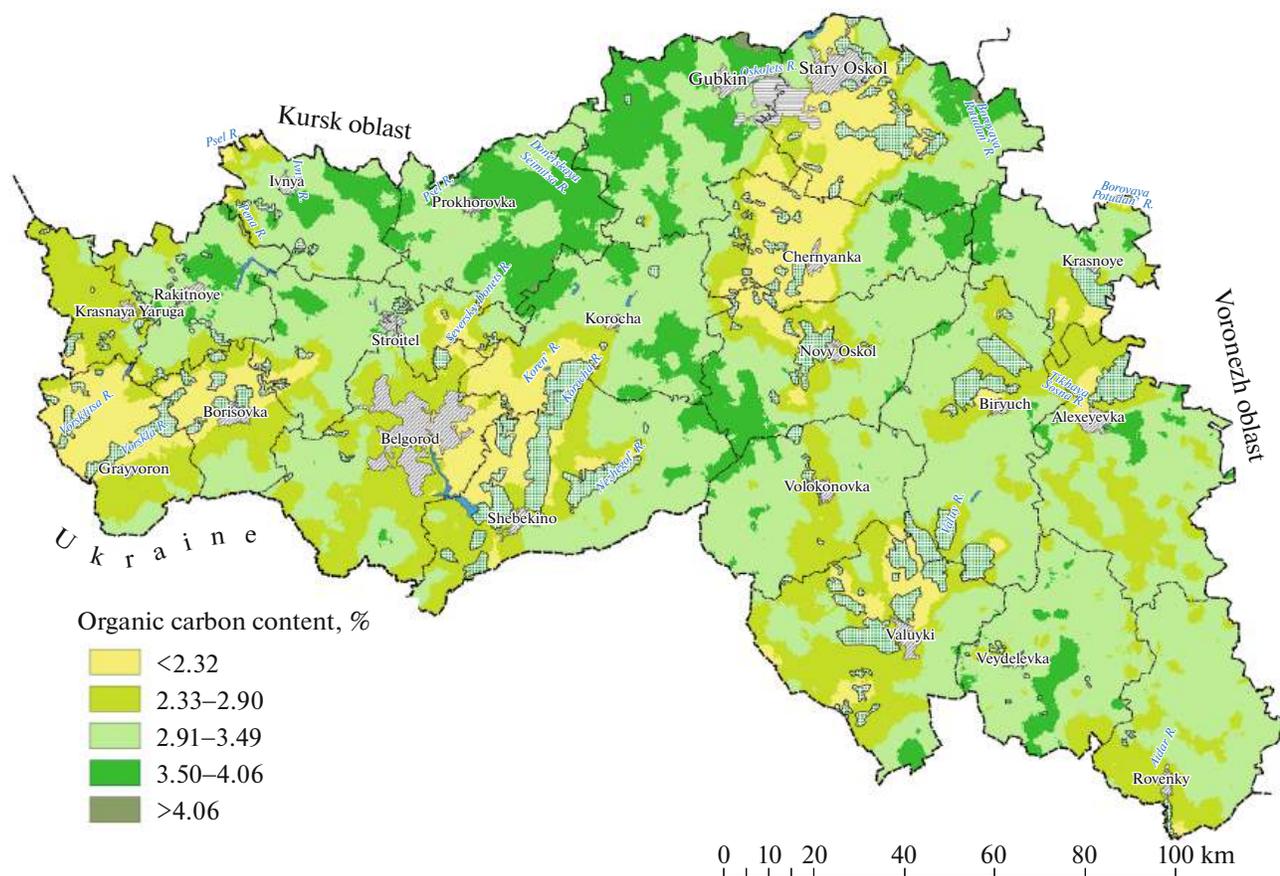
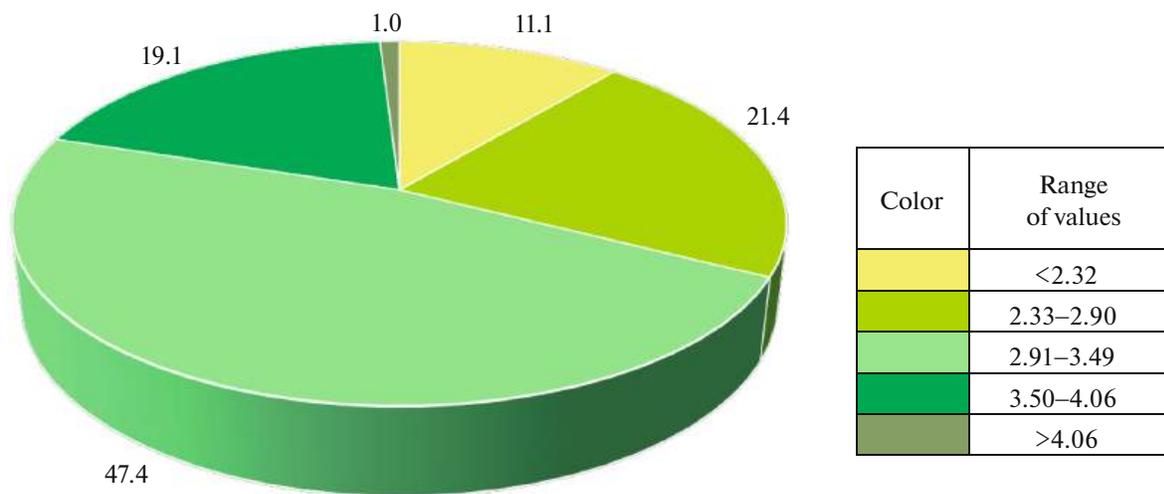**Fig. 3.** Cartogram of organic carbon content in arable soils.

Fig. 4. Distribution of soils by organic carbon content, % of the survey area.

In the soils of agroecosystems in the Central Chernozem region, the highest weighted average C_{org} content was recorded in the territory of Tambov oblast (3.77%), and the lowest one, in Kursk oblast (2.73%).

In the arable soils of Voronezh and Lipetsk oblasts, this parameter is 3.13 and 3.25%, respectively [8, 17].

Such positive dynamics is caused by an increase in the inputs of organic matter to the soils due to:

— a twofold increase (from 4.8 to 9.6 t/ha) in the rates of organic fertilizers;

— a 1.2−1.4-fold increase in the inputs of agricultural by-products owing to the improved crop yields;

— a widespread use of undersown sideral crops, which were not used before 2011, but in 2019−2022 their area accounted for 22% of the total sown area;

— a quite stable proportion (~15%) of grain-grass crop rotations, in which a positive C_{org} balance is formed by the plant residues of perennial grasses.

In addition, we implemented a set of measures to reduce C_{org} losses:

— a 2.7-fold reduction in the area of bare fallows where significant C_{org} losses occur (1.74 t/ha on average) due to mineralization of soil organic matter (SOM);

— a transition from plowing to minimum tillage, including the no-till technique on 24% of the sown area, which reduces SOM mineralization;

— adoption of adaptive landscape systems of farming on 90% of the territory, which substantially reduce C_{org} losses as a result of water erosion of soil.

The studied agroecosystems are dominated by soils (47.4%) with C_{org} in the range of 2.91−3.49%. The proportion of soils with higher C_{org} (3.50−4.06%) is 19.1%, while with C_{org} greater than 4.06% it is only 1.0%. The proportion of soils with C_{org} within 2.33−2.90% and below 2.32% are 21.4 and 11.1%, respectively (Figs. 3, 4).

As a rule, soil organic carbon content correlates closely with the content of easily hydrolyzable nitrogen, which largely determines the content of this important macronutrient in plants, especially without fertilizers [19, 20]. In our research, we established a direct linear relationship between the contents of C_{org} and easily hydrolyzable nitrogen (N_{eh}):

for the forest-steppe zone, $N_{eh} = 41.5 + 43.2C_{org}$ ($R^2 = 0.92$);

for the steppe zone, $N_{eh} = 54.6 + 37.9C_{org}$ ($R^2 = 0.86$).

CONCLUSIONS

Thus, our research established that typical and leached chernozems lost 40.0−42.0% of their organic carbon during the long-term use in agriculture compared to their counterparts in natural ecosystems. On average, for the studied subtypes of slightly washed-out chernozems, the decrease in the content of this parameter is 14.5−16.4% compared to unwashed arable soils. In the B horizon and the upper layer of the C horizon, the content of organic carbon was 1.87−2.22 and 5.30−6.98 times lower, respectively, than in the plow horizon. During the study period, the weighted average content of organic carbon in the arable soils of the region increased by 0.174%. Organic carbon stocks in the plow horizon increased by

5.22 t/ha on average, which corresponds to the accumulation of 19.1 carbon units/ha. This became possible due to the implementation of the comprehensive measures aimed at increasing inputs of organic matter to soils and reducing its losses. A direct linear relationship was established between the contents of organic carbon and easily hydrolyzable nitrogen in the soils.

CONFLICT OF INTEREST

The author of this work declare that he has no conflicts of interest.

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