Intake and fixation of organic carbon in grain agrophytocenosis of Western Siberia

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Abstract. In nature, carbon plays an important role in the circulation of organic matter in the soil-plant-atmosphere system. To understand the full picture of the farming system impact on carbon dioxide emissions, long-term stationary experiments are needed, which will reduce the influence of weather conditions on changes in organic carbon stocks in soils and develop an optimal model of the crop cultivation system considering the positive balance of organic carbon in soils. The research was carried out from 1995 to 2020 in the grain crop rotation at the station of the Department of Soil Science and Agrochemistry of the SAU of the Northern Trans-Urals, near vil. Utyashevo in the Tyumen region. Purpose. The purpose of the research was to establish the effect of increasing doses of mineral fertilizers on the intake and fixation of organic carbon with plant residues in the grain agrophytocenosis in the conditions of the forest-steppe zone of the Trans-Urals. The refusal to use mineral fertilizers leads to annual losses of organic carbon in the form of CO₂ up to 0.6 t/ha. The use of high doses of mineral fertilizers for the planned yield of 5.0 and 6.0 t/ha of grain annually increases the emission of CO₂ by 0.4-0.6 t/ha per year. In these variants, the carbon received from plant residues is not fixed in the soil. A positive balance of organic carbon is provided only by the use of doses of mineral fertilizers for the planned yield of 3.0 and 4.0 t/ha of grain, which annually increases the carbon stock in the soil by 0.4-0.6 t/ha, and up to 14-21% is fixed from the incoming organic carbon in the form of plant residues in the soil.

1. Introduction
Carbon is an element that binds the main components of agrocenosis into the soil-plants-atmosphere system during the cycle. In the photosynthesis process, atmospheric carbon accumulates in the main and by-products, and is also concentrated in the roots of agricultural plants. Depending on the direction of agricultural crop use, part of the carbon is alienated with the yield beyond the agrocenosis limits. The other one, concentrated in root and crop residues, returns to the soil. As a result of the transformation, part of the plant remains is preserved in the form of soil organic matter, thereby maintaining fertility. Part of the plant residues as a result of processing by soil biota, undergoes further transformation and passes into atmospheric carbon as a result of carbon dioxide emission [1]. Carbon losses in agroecosystems can occur with subsurface runoff of dissolved organic matter, nevertheless, the amount of such losses is many times lower than with CO₂ emissions, which is not considered in the balance assessment of organic matter [2]. Currently, the study of carbon dynamics in agroecosystems is gaining more and more interest. This is due to the fact that the soil is the main carbon reservoir, whose reserves are three times higher than in the aboveground biomass of plants and two times higher.
than in the atmosphere. Organic carbon, concentrated in the soil, is an important link in maintaining the fertility of arable land and the key to obtaining stable yields. Currently, many studies are being conducted to determine the dynamics of organic carbon stocks in soils of various agro-climatic zones [3-5]. The global study of this issue is primarily due to the fact that carbon distribution in agrocenoses depends more on soil and climatic conditions, the intensity of the farming system, the species composition of crops in crop rotation and the amount of chemicals and fertilizers used [6-8].

Currently, due to the need to increase the productivity of arable land for the world food security, the intensity of the use of mineral fertilizers has significantly increased, and with the transition to intensive crop cultivation technologies, the share of pesticides has increased, which has a negative impact on soil biota [9,10]. This leads to a violation of the composition of soil microorganisms and change in the intensity of the processes of organic matter mineralization and humification, which significantly changes the CO$_2$ emission, and the deficiency of organic matter increases sharply [11]. The rapid rejection of the use of organic fertilizers [12] leads to a sharp decrease in organic matter stocks in soils and increased carbon dioxide emissions [13]. Despite the variety of literary sources, there is no clear understanding of soil organic carbon dynamics depending on agrotechnological methods of cultivation of agricultural crops. This is due to the fact that such studies require long-term observations to correctly assess the direction of carbon transformation in the soil-plant-atmosphere system, smoothing the impact of annual changes in weather conditions. The available literature data show that carbon distribution in the soil-plant-atmosphere system plays a global role in creating a world model of carbon sequestration in soil and CO$_2$ emissions into the atmosphere, depending on tillage systems, fertilizer and plant protection systems.

The purpose of the research is to establish the effect of increasing doses of mineral fertilizers on the intake and fixation of organic carbon with plant residues in the grain agrophytocenosis in the conditions of the forest-steppe zone of the Trans-Urals.

2. Materials and Methods

The research was carried out on the experimental field of the State Agrarian University of the Northern Trans-Urals on the territory of the forest-steppe zone of the Tyumen region from 1995 to 2020 in the grain crop rotation (annual grasses - spring wheat - oat). The farming system has not changed over the years of the study and included the main dump tillage to a depth of 20-22 cm after precrop harvesting. In the spring, on physically fermented soil, they harrowed with medium harrows in two tracks. Before sowing, doses of mineral fertilizers were applied to the planned yield of spring wheat and oat (the calculation was carried out annually by the elementary balance method, considering actual content of nutrients in the soil), fertilizers were not applied for annual grasses. Ammonium nitrate (34% nitrogen) and ammonphoska (N12:P12:K12) were used as fertilizers. After applying mineral fertilizers, pre-sowing cultivation was carried out to a depth of 6-8 cm. In the future, they were sown after rolling with star-wheel rakes. The seeding rate of spring wheat and oat is 6.0 million germinating seeds per hectare. The experiment included variants with the introduction of mineral fertilizers for the planned yield of 3.0; 4.0; 5.0, and 6.0 t/ha of spring wheat and oat, the variant with the natural fertility of leached chernozem was used as a control. The size of the experimental plots is 100 m$^2$, accounting plots - 50 m$^2$. The experiment was laid down in a four-fold repetition, the plots are fixed. To account the straw mass yield, sheaves from 1 m$^2$ were selected in four-fold repetition before harvesting. In the future, the grain was threshed with sheaf threshers, after which the straw was weighed. Determination of the root and crop residues was carried out annually by the method of N.Z. Stankov. A 30 cm thick soil layer was selected through a 0.25 m$^2$ frame, after which it was washed through a 0.25 mm mesh sieve and the mass of plant residues was considered. Further, in the samples of straw, crop and root residues, the content of organic carbon was determined according to GOST 27980-88. To determine the mass fraction of organic carbon, the dry residue of the sample is used after determining the mass fraction of moisture. After careful mixing, a sample is taken from the dry residue from at least five suspension points for analysis. The suspension weight should be 3 g. Weighing is carried out with an error of no more than 0.001 g. Then calcination is carried out at a temperature of 800°C until
ash is obtained. The mass fraction of organic matter in terms of carbon (X) as a percentage is calculated according to the formula:

\[ X = (100 - A) \times 0.5 \]  

where:
- A - mass of ash after calcination, %
- 0.5 - coefficient for carbon conversion.

To determine the reserves of organic carbon in the soil in each variant, soil samples were taken in layers every 10 cm to a depth of 1 meter. The content of organic carbon in the soil was determined according to GOST 26213-91. The method is based on the organic matter oxidation with a solution of potassium bicarbonate in sulfuric acid and the subsequent determination of trivalent chromium, equivalent to the content of organic carbon, on a photoelectric colorimeter. In the future, the calculation of organic carbon reserves was carried out in layers, considering the bulk density. Statistical data processing was carried according to Dospekhov using Microsoft Excel software.

3. Results and Discussion

Plant residues are a source of organic matter entering the soil. Straw, crop and root residues (CRR) are the main component of soil replenishment with organic carbon in the grain agrophytocenosis. Straw accounts for almost half of all incoming plant residues in the soil in the grain crop rotation. The farming system, which involves the collection of straw from the fields after harvesting grain crops, leads to a decrease in the intake of organic matter into the soil and, as many long-term studies show, leads to a shortage of organic carbon in the soil [14,15].

It was found that in the variant without the use of fertilizers from 1995 to 2005 18 t/ha (LSD05 = 2 t/ha) of plant components entered the soil with straw, crop and root residues accounted for 25 t/ha (LSD05=3 t/ha) (Fig.1).

![Figure 1. Dynamics of the intake of plant residues, t/ha.](image_url)

In the variant using NPK for 3.0 t/ha of spring wheat and oat, the amount of incoming plant residues for the period from 1995 to 2005 increased by 17% relative to the control and reached 50 t/ha. A further increase in the level of nutrition naturally increased the yield of straw, crop and root residues...
by 35-53% relative to the control due to increased photosynthetic activity of plants and increased biomass of the main and by-products.

From 2005 to 2015, the amount of organic residues received at the control decreased to 38 t/ha, this happened because since 2005, a variety changing has been carried out in the crop rotation. In the variants with the introduction of mineral fertilizers for the planned yield from 4.0 to 6.0 t/ha of wheat and oat, the amount of plant residues increased by 7-11% relative to the previous period. This is due to the fact that the grain varieties used from 2005 to 2015 belong to the intensive type varieties that respond well to the high level of the agricultural background.

Since 2015, spring wheat and oat varieties have been replaced with more productive ones again. These varieties respond better than their precrops to an increased level of mineral nutrition and have a large vegetative mass, which enhances the photosynthetic activity of crops and increases the development of the root system. As a result, in 5 years since 2015, 9 tons/ha of straw and 15 tons/ha of crop and root residues have entered the soil with plant residues, which is 10-21% higher than in the previous five-year periods. There is a particularly strong increase in crop and root residues on fertilized variants. The values of which for five years were higher than the previous values for the same period by 6-14 t/ha. The mass of straw entering the soil was 5-29% higher than the previous values for a period of five years. Based on the data obtained, it can be concluded that when programming the amount of organic residues entered into the soil, it is necessary to consider not only agricultural crops in crop rotation, but also the varietal feature of agricultural crops.

Plant residues, depending on soil and climatic conditions and biological characteristics of crops, contain a significant amount of nutrients in their composition. 1 ton of dry matter contains 4.7-11.1 kg of nitrogen, 2.1-5.2 kg of phosphorus, 18.9-32.0 kg of potassium, 1.1-10.2 kg of calcium, 0.6-5.6 kg of magnesium, and 470-480 kg of carbon, which are the main source of increasing soil fertility [16].

In the period from 1995 to 2005, 20 t/ha of organic carbon was added to the soil on the variant without the use of fertilizers in the grain agrophytocenosis (Fig. 2).

![Figure 2](image-url)  
*Figure 2. Input of organic carbon into the soil with plant residues, t/ha.*
The introduction of mineral fertilizers for the planned yield of 3.0 t/ha of spring wheat and oat grain increased the intake of organic carbon into leached chernozem by 20%, during the first 10 years of the study. A further increase in the level of mineral nutrition increased the intake of organic carbon into the soil by 40-55% relative to the control, where these values reached 28-31 t/ha (LSD$_{0.05}$ = 2 t/ha). The increase in the return of organic carbon to the soil on fertilized variants is primarily due to an increase in the leaf surface of crops, an increase in photosynthetic activity, an increase in the yield of main and by-products, and second, a decrease in the content of ash elements in them [17-19].

The transition in 2005 to the cultivation of varieties of spring wheat and intensive oat provided responsiveness to high doses of mineral fertilizers. As a result, in variants with the introduction of NPK above 4.0 t/ha of grain, the intake of organic carbon with plant residues naturally increased. In the period from 2005 to 2015, these values increased by 3-10%. At a low agricultural background (NPK at 3.0 t/ha), no differences were observed, whereas at the control, 10% less organic carbon entered the soil.

During the last period of research from 2015 to 2020, there was an increase in the intake of organic carbon with plant residues in all the studied variants. On the control during 5 years of research, 11 tons/ha of organic carbon entered the soil, which is one ton higher than during the same time in the first two periods of research. With an increase in the level of mineral nutrition, there is a significant increase in the intake of organic carbon into the soil. The 3.0 t/ha NPK variant received 16% more organic carbon from 2015 to 2020 than in the previous five-year periods. In the variants with the introduction of mineral fertilizers up to 5.0 t/ha of grain over the past 5 years, 17 and 33% more were received than in the previous corresponding periods. A further increase in the level of nutrition led to an increase in carbon intake by 30% relative to the corresponding previous accounting period.

Organic carbon in soils is one of the most important fertility indicators. The intensity of the use of lands involved in agricultural use leads to a decrease in the organic soil matter reserves [20]. This leads to deterioration of the water regime, erosion resistance of the soil, and decrease in nutrients [21,22]. Increasing and stabilizing carbon stocks in soils is an important task in the conditions of modern carbon-saving agriculture [23].

In the leached chernozem before the experiment, the organic carbon stocks in the meter layer were 234-239 t/ha. The farming system without the use of fertilizers for ten years led to a decrease in carbon stocks by 5 t/ha (LSD$_{0.05}$ = 1 t/ha). The transition to more intensive varieties of grain crops reduced the output of by-products, as a result, from 2005 to 2015, the reduction in carbon stocks amounted to 3.5%, which is 3 t/ha more than the previous period. From 2015 to 2020, carbon stocks continued to decrease from 226 to 224 t/ha in the fertilizer-free variant (Fig.3).

![Figure 3. Dynamics of organic carbon stocks in a meter layer of leached chernozem, t/ha.](image-url)
In the variants with the introduction of mineral fertilizers for the planned grain yield of 3.0 t/ha, positive dynamics was noted. During the first 10 years of arable land use on this variant, the organic carbon stocks increased by 4 t/ha. A favorable trend was also observed in the variant with the introduction of NPK for 4.0 t/ha of grain crops, where carbon stocks increased by 2 t/ha. From 2005 to 2015, the organic matter stocks increased by 6 t/ha on the variant with the introduction of NPK for 3.0 t/ha, and on the variant with NPK for 4.0 t/ha for 5 t/ha. The tendency of increasing carbon stocks in leached chernozem was noted until the end of the research. Based on the data obtained, it can be concluded that the fertilizer system designed to produce 3.0 and 4.0 t/ha of spring wheat and oat grain provides an increase in organic carbon reserves due to the amount of plant residues received and soil biota intensity. In the variants with the introduction of fertilizers for the planned crop yield of 5.0 and 6.0 t/ha of grain, the opposite pattern was noted. During the first 10 years of accounting, the organic matter stocks decreased by 2.0-2.5% relative to the initial values. From 2005 to 2015, the dynamics of organic carbon stocks continued to follow the negative dynamics at high agricultural backgrounds. Nevertheless, the carbon reduction was lower than in the previous accounting by 1-2 t/ha. This is also due to the peculiarity of the varieties used in different accounting periods.

From 1995 to 2020, on the variant without the use of mineral fertilizers, the organic carbon stocks decreased by 15.5 t/ha. Annual carbon losses from the soil amounted to 0.6 t/ha. A negative balance was also observed in the variants with carrying NPK for 5.0 and 6.0 t/ha of grain, stocks decreased by 14 and 10 t/ha during the study period, which corresponds to an annual loss of organic carbon by 0.6 and 0.4 t/ha (Fig. 4).

![Figure 4. Balance of organic carbon stocks in a meter layer of leached chernozem, t/ha.](image)

A positive balance was noted in the variants with the introduction of mineral fertilizers for the planned yield of 3.0 and 4.0 t/ha of spring wheat and oat, where the organic carbon stocks increased by 11 and 9 t/ha during the study period, which corresponds to an annual increase of 0.4 t/ha.

The incoming carbon in the form of plant residues does not completely remain in the soil, most of it, as a result of mineralization processes, it passes into the gaseous form of carbon dioxide and returns to the atmosphere [24].

It was found that the annual losses of organic carbon, considering its intake into the soil with plant residues, amount to 2.6 t/ha at the control, which corresponds to losses of 124% of the total intake of organic carbon into the soil (Fig. 5). The use of a fertilizer system designed to produce 3.0 t/ha of spring wheat and oat reduced the total loss of organic carbon to 2.1 t/ha. At the same time, no more than 79% of the organic carbon entering the soil was converted into CO₂. Despite the fact that in the
variant with NPK for 4.0 t/ha of grain, the total carbon loss was 2.7 t/ha per year, due to the higher biomass of by-products in this variant, 14% of the incoming carbon with plant residues was fixed in the soil. The introduction of increasing doses of mineral fertilizers activates the soil microflora and enhances the mineralization process [25]. This leads to an increase in organic carbon losses in the variants with NPK for 5.0 and 6.0 t/ha of grain to 4.1 and 4.0 t/ha, which corresponds to losses of 114 and 110% of the total carbon intake into the soil for the year.

\[\text{Figure 5. The effect of increasing doses of mineral fertilizers on the loss of soil and organic carbon received with plant residues in grain agrophytocenosis, t/ha.}\]

To maintain the organic carbon stocks in the soil on variants with a negative balance, it is necessary to provide additional organic fertilizers in the form of chicken manure, which contains up to 37% carbon, so on variants with NPK for 5.0 and 6.0 t/ha of grain, annual application of up to 11-12 t/ha of chicken manure is necessary. Such a dose will optimize the carbon balance of leached chernozem. Nevertheless, do not forget that due to the additional organic matter received, the microbiological activity of the soil and the mineralization process will increase, which will lead to increased CO₂ emissions in agroecosystems.

4. Conclusions
Cultivation of agricultural crops in grain crop rotation without the use of mineral fertilizers leads to a deficient balance of organic carbon in the soil. Annually, up to 0.6 t/ha of organic carbon from leached chernozem is lost in the form of CO₂ in these variants. About 124% of the organic carbon entering the soil in the form of straw and root and crop residues is lost in the form of CO₂. The use of mineral fertilizers for the planned yield from 3.0 to 4.0 t/ha of spring wheat and oat provides a positive balance of organic carbon in the soil. The annual increase is 0.4 t/ha. At the same time, on these variants, from 14 to 21% of the organic carbon received with plant residues is fixed in the soil. The use of high doses of mineral fertilizers for the planned grain yield of 5.0 and 6.0 t/ha also negatively affects the balance of organic carbon stocks in the soil, the decrease reaches 0.4-0.6 t/ha per year. At the same time, 110-114% of the incoming carbon with plant residues passes into carbon dioxide.

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