Balance model of humus state of arable chernozems of the Western Siberia

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Abstract. The results of model simulation of the humus state of arable soils in the Western Siberia based on long-term stationary studies and agrochemical monitoring of agricultural lands are presented. The following were studied: leached chernozem; podzolized chernozem; meadow-chernozem and dark gray forest soils. It was found that the nature of the root system formation depends on the biological characteristics of crops and cultivation conditions (the level of mineral nutrition, moisture). The mass of crop-root residues, as well as straw, is in close correlation with the yield of grain crops. Based on the actual data, regression equations were obtained with a high degree of reliability of the calculated data (approximation coefficient from $R^2 = 0.84$ to $R^2 = 0.93$). Using the balance model of humus formation, it was found that the podzolized chernozem and dark gray forest soil were the least resistant to the anthropogenic factor. As a result of prolonged agricultural activity (52 years), humus losses in them amounted to 28 and 37 t/ha, which corresponded to annual losses of 0.54 and 0.71 t/ha. Leached arable chernozems lost 24 t/ha of humus, which corresponded to annual losses of 0.46 t/ha. In the course of the study, it was revealed that the arable land of the Western Siberia has a stable negative balance of humus state, which requires optimization of the farming system in the region.

1. Introduction

It is well known that humus is the most important soil component. It is synthesized annually in the soil, but at the same time it is actively mineralized to inorganic compounds. In natural biocenoses, the humus dynamics is stable and is determined by external factors, which include water, salt, and temperature regimes [1, 2, 3]. The organic matter formed during photosynthesis in biocenoses eventually enters the soil and is processed by microorganisms [4, 5]. The process of transformation of plant residues on virgin land has been well studied. Mathematical models of humus formation have been compiled, the reliability of which has been practically proven.

For soils involved in agricultural turnover, the problem of forecasting is extremely acute. Science has only actual data on the dynamics of humus in the fields for 50-100 years, but it cannot make long-term forecasts yet. In agroecosystems, anthropogenic impact is imposed on natural factors. First of all, this is the alienation of marketable products from the field. Enterprises of the agro-industrial complex, when growing grain crops, export grain and straw from the fields. Only postharvest-root residues remain in the soil, the mass of which is significantly less than the roots of perennial grasses. The use of mineral fertilizers also leaves its mark on the humus state of the arable land. The biomass of agricultural crops is increasing, but the activity of the soil microbiota is also increasing [6, 7]. This leads to the fact that cellulose-decomposing fungi and bacteria very quickly mineralize plant residues.
in the soil and the process of humus destruction begins. Studies of the State Agrarian University of the Northern Trans-Urals have shown that the introduction of high doses of fertilizers (more than 150 kg/ha of nitrogen annually) enhances the mineralization of humus in a layer of 0-50 cm of leached chernozem [8, 9]. The humus state is affected by mechanical tillage. It affects different natural and climatic zones in different ways. Therefore, the recommendations for the preservation of arable land fertility developed in the European zone of Russia, especially in its steppe regions, will be ineffective for the Western Siberia and much more for the Far East [10].

With the accumulation of knowledge on the transformation of soil organic matter, it became possible to develop humus balances based on mathematical modeling [11]. Balance calculations allow to accurately determine the direction of transformation of humus substances and develop a highly efficient fertilizer system that provides expanded reproduction of fertility. The development of a balance model has become possible even for a single field, which is extremely important for an agricultural producer.

The humus balance is calculated by comparing the annual intake of plant residues into the soil and the loss of humus from it. When compiling the humus balance, it is necessary to consider not only the quantity, but also the quality of plant residues entering the soil. An increase in the total nitrogen content in them affects the rate of decomposition and formation of humic substances [12, 13]. The location of plant residues and organic fertilizers in the soil determines which processes will dominate - mineralization or humification [8, 13]. The expense item in the balance model also has its own characteristics. Traditionally, it considers the mineralization of humic substances under agricultural crops and fallows. Losses due to wind and water erosion can also be calculated mathematically. Recent studies have also shown that it is necessary to clarify certain elements of the expense item. A wide range of tillage systems in the fields (mouldboard, subsurface, minimal or No-till) affect the mineralization process in different ways, creating certain conditions for the vital activity of the soil microflora.

The purpose of our work is to study the features of the elements of the balance model of humus formation of chernozem soils of the Western Siberia.

2. Materials and Methods
When compiling the balance model of humus formation of arable soils, generally accepted correction coefficients were used, as well as the results of their own long-term research on the experimental field of the State Agrarian University of the Northern Urals. The experimental field is located in the northern forest-steppe of the Tyumen region. The soil of the site is leached chernozem, thin, medium-humus, heavy loamy. The soil-forming rock is casing carbonate loams and clays. Various types of soil tillages and crop rotations have been studied at the experimental field since 1975. They cereals (winter and spring wheat, oat, barley); row crops (potato, corn) and perennial grasses (variegated alfalfa, awnless brome, timothy) are cultivated. Over the years of research, a full-fledged digital material was obtained, which formed the basis for compiling balance models of the humus state of arable land.

In this paper, the calculation of humus consumption was carried out by biogenic removal of half the amount of nitrogen with the following correction factors.

The humus consumption under close-growing crops (cereals) is 1.2; for row crops - 1.6. For soils of heavy granulometric composition, the correction factor was 0.8; medium-loamy - 1.0; light-loamy 1.2. Losses of soils and humus from surface wash were established considering the terrain slopes according to the following gradation: the slope of the field is up to 1° - 0.5 mm; 1-3° - 1.5 mm; more than 3° - 3 mm annually. Calculations of humus reserves were carried out considering the density of the soil and the humus content in the arable layer.

The incoming part of organic matter in the form of straw and crop-root residues was determined according to generally accepted methods. The data obtained formed the basis for the compilation of regression equations necessary for the compilation of the balance model. The following humification coefficients were provided for plant residues: cereals, annual and perennial grasses - 0.2; corn - 0.1.
The volume of root secretions in the income was taken at the rate of 10% of the total phytomass of crops with a humification coefficient of 0.2.

3. Results and Discussion

Studies conducted at the experimental field of the State Agrarian University of the Northern Trans-Urals, have shown that the incoming mass of by-products (plant residues) varies by species in quantitative terms. With the same yield, winter wheat forms 4.3 t/ha of straw and 2.7 t/ha of roots (Table 1). Other grain crops are significantly inferior to it in terms of the yield of plant residues. After harvesting spring wheat with a yield of 2.0 t/ha, 2.5 t of straw remains on the field; 0.4 t of crop residues and in a soil layer of 0-30 cm – 1.3 t/ha of roots. The total mass of plant residues, with a minimum yield, reaches 4.2 t/ha, which is 45% less than that of winter wheat. The yield of oat by-products (straw) is higher than that of spring wheat and barley [14]. With a grain yield of 2.0 t/ha, 3.4 t of straw remains in the field, whereas after barley – 2.9 t/ha.

Mineral fertilizers are a powerful factor in increasing yields at minimal cost. No agrotechnological technique (tillage, crop tending) or variety gives such an effect as an artificial increase in the level of mineral nutrition. Currently, agrochemistry can offer production a differentiated method of applying mineral fertilizers, ensuring stable receipt of the planned crop yield [13]. Our studies have shown that with increasing yields, the yield of by-products naturally increases, but the ratio of grain/plant residues depends on the biological characteristics of grain crops.

With a yield of 6.5 t/ha of winter wheat grain, the straw weight reaches 12 t/ha - grain:straw ratio is 1.85, whereas at 2.0 t/ha of grain - 2.15 units. Fertilization also affects the formation of the root system and, as our research has shown, the increase in mass is not directly proportional to the increase in the yield of marketable products. With the formation of 2.0 t/ha of grain on the variant without the use of fertilizers, the root weight was 2.7 t/ha, which is 1.35 times more than the yield. In the fertilized version, where the grain yield was 6.5 t/ha, the root weight was equal to the yield.

A somewhat different situation was observed in spring grain crops. Spring wheat with a grain yield of 1.6 t/ha had 2.5 tons of straw and 1.7 tons of postharvest-root residues, 1.3 of which were roots. This is significantly less than that of winter wheat. Fertilization provided grain production up to 6.3 t/ha, but with a smaller weight of straw (7.2 t/ha) and postharvest-root residues (7.9 t/ha). The total weight of by-products remaining after spring wheat harvesting was 15.1 t/ha, which is 28% lower than winter wheat.

| Agricultural crops | Commodity yield, t/ha | Secondary straw | surface residues | roots | Total | Postharvest-root residues |
|--------------------|-----------------------|-----------------|------------------|-------|-------|--------------------------|
| Winter wheat       | 2.0                   | 4.3             | 0.7              | 2.7   | 7.7   | 3.4                      |
|                    | 4.5                   | 8.7             | 1.5              | 6.3   | 16.5  | 7.8                      |
|                    | 6.5                   | 12              | 2.6              | 6.5   | 21.1  | 9.1                      |
| Spring wheat       | 1.6                   | 2.5             | 0.4              | 1.3   | 4.2   | 1.7                      |
|                    | 4.2                   | 5.8             | 1.2              | 4.8   | 11.8  | 6.0                      |
|                    | 6.3                   | 7.2             | 2.3              | 5.6   | 15.1  | 7.9                      |
| Barley             | 1.8                   | 2.9             | 0.3              | 2.5   | 5.7   | 2.8                      |
|                    | 3.4                   | 4.6             | 1.6              | 4.1   | 10.3  | 5.7                      |
|                    | 5.3                   | 6.2             | 2.1              | 5.3   | 13.6  | 7.4                      |
| Oat                | 2.1                   | 3.4             | 0.6              | 2.8   | 6.8   | 3.4                      |
|                    | 3.8                   | 6.1             | 1.7              | 6.1   | 13.9  | 7.8                      |
|                    | 5.7                   | 7.3             | 3.1              | 5.7   | 16.1  | 8.8                      |
| Annual grasses (pea-oat mixture), green mass | 15 | 0 | 0.8 | 2.8 | 3.6 | 3.6 |
|                    | 28                   | 0               | 1.7              | 3.7   | 5.4   | 5.4                      |
The use of sown fallow in the system of modern crop rotations is based on the cultivation of annual cereals for green mass or haylage. A feature of this use is the absence of straw, which could be used to enrich the arable land with plant residues. As a source of organic matter, only postharvest-root residues remain, the weight of which is 3.6-5.4 t/ha. This is comparable to grain crops grown at a moderate level of mineral nutrition. In the fields where straw is plowed, the intake of plant residues is significantly 1.5-2.5 times higher than it remains after annual grasses. Thus, in the absence of additional use of organic fertilizers, sown fallows created by sowing a mixture of grain and leguminous crops will not provide a positive balance in crop rotation.

On a natural agricultural background (without the use of fertilizers), barley and oat have certain advantages over spring wheat. Their root system is significantly larger and therefore the absorption of nutrients and water is more efficient. Fertilization affects the formation of the root system in different ways. With a yield of 5.3 t/ha of barley, the ratio of postharvest-root residues to grain is 1.4 units, which is comparable to the indicators of spring wheat. A decrease in the level of agricultural background (yield 3.4 t/ha) has a stimulating effect on the development of the root system (the ratio is 1.7 units).

Oat stands out among other spring cereals with a more powerful root system. This is its biological feature, which has been significantly enhanced as a result of long-term breeding [15, 16], depending on the level of mineral nutrition, it varies from 2.8 to 6.1 t/ha. It was found that with an increase in the agricultural background, which provides grain production up to 4.0 t/ha, oat actively increases its root system - the ratio of PRR/grain is the maximum among the studied crops and reaches 2.1 units. A further increase in the level of mineral nutrition (yield 6.0 or more t/ha) leads to a decrease in root weight, without reducing grain yield.

Thus, we have established the biological features of the formation of the root system of grain crops and the output of by-products per unit area. The yield of plant residues (straw+PRR) has a direct positive relation with yield. The use of averaged coefficients for recalculating the weight of straw and crop-root residues through the yield of commercial products of continuous sowing crops, without considering their biological characteristics, will lead to distortion of the results of the balance model of humus formation.

As a result of regression analysis, the corresponding equations were obtained, which can be used to calculate the receipt of plant residues after growing grain crops. The calculation method is appropriate when determining the weight of crop-root residues, since it is not possible to determine them in production conditions, unlike straw. The regression equations are presented in Table 2.

**Table 2.** Regression equations for calculating the weight of crop-root residues of cereals and annual grasses.

| Crops                      | Equation          |
|----------------------------|-------------------|
| Winter wheat               | \( Y = 1.29x + 1.19 \) |
| Spring wheat               | \( Y = 1.33x - 0.45 \) |
| Barley                     | \( Y = 0.75x + 1.30 \) |
| Oat                        | \( Y = 1.30x + 0.94 \) |
| Annual grasses (pea-oat mixture) | \( Y = 0.10x + 2.14 \) |

Where: \( Y \) is the weight of crop-root residues, t/ha
\( x \) – commercial products (grain or green mass), t/ha.

The compiled equations are reliable up to the yield of grain crops of 6.5 t/ha and the weight of annual grasses - 40.0 t/ha. The calculated results almost completely coincide with the actual values of crop-root residues.
Using generally accepted coefficients and regression equations compiled by us, the humus balance in the main soils of the forest-steppe zone of the Western Siberia was calculated (Table 3). The calculation was carried out over three-time intervals:

1968-1990 The agriculture period in the USSR. At that time, agriculture was actively developing in the Western Siberia. Modern soil processes were actively studied, new varieties adapted to the unfavorable soil and climatic conditions of the region were created and a regional fertilizer system was developed. During this period, mineral fertilizers were actively used, and organic fertilizers were systematically applied – manure, humus, peat and sapropel. Straw was mainly exported from the fields to livestock farms.

| Soil subtype           | 1968-1990 | 1991-2005 | 2006-2020 |
|-----------------------|-----------|-----------|-----------|
|                       | Expenditure | Receipt | Balance | Expenditure | Receipt | Balance | Expenditure | Receipt | Balance |
| Leached chernozem     | 44         | 35        | -9       | 34         | 23       | -11      | 34         | 30       | -4      |
| Podzolized chernozem  | 40         | 30        | -10      | 31         | 21       | -10      | 36         | 28       | -8      |
| Meadow-chernozem      | 40         | 32        | -8       | 29         | 24       | -5       | 37         | 35       | -2      |
| Dark gray forest      | 42         | 28        | -14      | 33         | 20       | -13      | 40         | 30       | -10     |

1991-2005 The period of agriculture destruction. It was characterized by the absence of mineral fertilizers. Organic fertilizers were not applied to the fields, for organizational and economic reasons. Straw, like grain, was a commercial product and was exported for sale.

2006-2020 The period of agriculture restoration and the introduction of digital technologies into it. Mineral fertilizers were applied to the planned harvests. Organic fertilizers have been reintroduced in advanced farms. Straw was mainly crushed and plowed.

As the calculations of the balance models of the humus state of arable land showed, in the period from 1968 to 1990, the expenditure part of humus was 40-44 t/ha, depending on the soil type. The annual mineralization of humus varied from 1.8 to 2.0 t/ha. Due to the receipt part of humus formed during the transformation of plant residues and organic fertilizers, partial compensation of humus losses occurred. Nevertheless, this was not enough to stabilize the humus state. A negative balance was observed on all soil subtypes. During the period 1968-1990, soils lost from 8 to 14 t/ha of humus from the arable layer. The greatest losses were in the dark gray forest soil, where they reached 14 t/ha. The annual loss of humus on this soil was equal to 0.63 t/ha per year.

In the years when mineral fertilizers were absent and straw was exported from the fields (1991-2006), the receipt part decreased to the minimum values. During this period, it reached 20-24 t/ha. The expenditure part has also decreased, due to the lack of mineral fertilizers and the rejection of some mechanical soil tillage. The humus balance during this period was also negative. Humus losses for the period 1991-2005 amounted to 5-13 t/ha. The minimum negative balance was only in meadow-chernozem soils, where the mineralization of plant residues was lower than in other soils, due to lower temperature in the arable layer. Nevertheless, due to the presence of humus substances in the subsurface layer, a higher yield was formed, even relative to leached chernozem.

For 2006-2020, as the balance model showed, the expenditure part of humus has not undergone significant changes. Depending on the soil subtype, it varied from 34 to 40 t/ha. The receipt part increased by 25-30% relative to the previous period. This is due to the increase in yields due to new technologies and the use of mineral fertilizers. But, despite this, the humus balance remained negative,
although it was close to the equilibrium state between the receipt and expenditure items on meadow-chernozem soils. This corresponded to a simple reproduction of soil fertility. For a positive balance of humus, it would be enough to increase the supply of plant residues in the form of organic fertilizers.

Figure 1 shows the annual loss of humus of arable soils in the previously specified time intervals. In the period from 1968 to 1990, annual losses in the arable layer were in the range of 0.4-0.6 t/ha. The greatest losses were on dark gray forest soils. In the years from 1991 to 2005, annual losses increased only on leached chernozems and dark gray forest soils, where they amounted to 0.7 and 0.8 t/ha, respectively.

![Figure 1. Annual loss of humus in the arable soil layer of the south of the Tyumen region, t/ha.](image)

Calculations have shown that from 2006 to the present in the arable layer of leached chernozem, the annual loss of humus is minimal - 0.3 t/ha, which is due to the high culture of agriculture, which ensures a stable supply of plant residues on arable land. Even better indicators of humus balance were noted on meadow-chernozem soils, where the annual loss was 0.1 t/ha, which is the minimum among the studied soils.

The annual loss of humus on the chernozems of podzolized and dark gray forest soils amounted to 0.6-0.7 t/ha, which is comparable with the previous time interval. This fact is due to the manifestation of natural soil formation processes that negatively affect humus formation (increased aeration of the arable horizon due to a lighter granulometric composition) [17, 18]. Therefore, for these subtypes, it is necessary to apply an individual approach to their use in arable land, by choosing a system of crop rotations, with crops having a higher yield of plant residues. It can also be proposed to change the tillage system to reduce the aeration of the arable layer and thereby reduce the microbiological activity of the soil.

4. Conclusion
The loss of humus in the arable soils of the Western Siberia is stable. As the analysis of the balance model showed, from 1968 to 2020, leached arable chernozems lost 24 t/ha of humus, which corresponded to annual losses of 0.46 t/ha. The humus balance of meadow-chernozem soils was less significant – during the same period, a humus deficit of 15 t/ha was formed in the arable layer. Annual losses amounted to 0.28 t/ha. The podzolized chernozem and dark gray forest soil proved to be the least resistant to the anthropogenic factor. As a result of prolonged agricultural activity (52 years), humus losses amounted to 28 and 37 t/ha, respectively. Annual losses are 0.54 and 0.71 t/ha. The data obtained during the calculation using regression equations almost completely coincide with the actual
values of the humus content in the studied soils (approximation coefficient from $R^2 = 0.84$ to $R^2 = 0.93$). The equations can be used in the system of forecasting the fertility of arable soils and in the development of an adaptive landscape farming system that considers the soil-climatic and socio-economic conditions of the region.

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