

The Evolution Of The Chernozems In The Central Part Of Russia And Their Complex Analysis In Modern Conditions

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Abstract

An increasing anthropogenic impact on soils leads to qualitative and quantitative changes in chernozems, the richest soils on Earth. In this regard, the understanding of modern soil-forming processes is undoubtedly relevant because it will allow predicting the future state of not only soils, but also nature as a whole.

The methodology for studying the evolution of chernozems is based on a process-factor analysis of genetically conjugated and agrogenic series of chernozems of different taxonomic levels. The objects of the study were system complexes of soil series, including subtypes of virgin, arable, and irrigated chernozems in the central regions of Russia. The data obtained made it possible to identify patterns of variation in the composition and properties of virgin chernozems in a genetically conjugated series at a subtype level and in the series virgin land – arable land – irrigated arable land; we also detected the processes and factors that determine the nature and direction of changes in the composition and properties of chernozems in the studied series and determined the direction of anthropogenic evolution of chernozems.

The main provisions of the work conceptually develop the theory of the chernozem-forming process and serve as a theoretical basis for the development of models for the formation of the chernozem profile. Established quantitative and qualitative indicators of humus profiles of chernozems are important diagnostic features in the classification of these soils. The nature and direction of the chernozem evolution disclosed in the work can serve as the basis for long-term forecasting of the state of these soils and the development of a set of measures for their rational use and protection.

Keywords: chernozem, soil formation, soil types and subtypes, morphological characters, composition, properties, humus profile, anthropogenic evolution.

1. Introduction

In Russia, chernozems occupy an area of approximately 120 million hectares. This is only 7% of the country's area, but this territory comprises more than half of Russian arable land that yields approximately two-thirds of all agricultural products produced in the country (Scherbakov, 2001).

Chernozem is a soil benchmark most clearly and fully reflecting the factors of soil formation and soil properties. V.V. Dokuchaev called it the "king" of soils. But the natural perfection of chernozem cannot withstand the accelerating process of modern soil evolution under the influence of natural and anthropogenic factors. The anthropogenic variability of soils is based on the violation of the quasi-

equilibrium state between the factors of soil formation and the processes that make up the essence of soil formation. Human economic activity mainly focuses on soil climate and biota. We also witness direct or indirect influence of anthropogenesis on other factors. The purpose of this study was to analyze the current state of chernozems and scientifically substantiate the direction of their evolution under conditions of agrogenesis.

2. Materials and methods

The issues of soil evolution have been relevant in soil science since the publication of V.V. Dokuchaev's works. However, they were reflected in the works of many other researchers (Aleksandrovsky, 1984; Gennadiev, 1986; Gerasimov, 1968; Rozanov, 2004). But under present conditions of an increasing anthropogenic impact on the environment, the issue of transformation of soil resources is becoming especially acute (Gennadiev and Ivanov, 1989). Despite the importance of this problem, it still has no unambiguous solution due not so much to the complexity of the problem itself as to the lack of methodological support, i.e. the impossibility of reconstructing the state of soils in a single chronological series. A large number of modern scientific approaches and methods are aimed at studying the evolution of soils (Gennadiev, 1978; Gennadiev and Ivanov, 1989; Scherbakov, 2001), although it should be recognized that none of them provides an unambiguous interpretation of the issue in question – they only allow formulating hypotheses (Rozanov, 2004).

Due to the complexity and the relevance of the problems, the studies of natural and anthropogenic chernozem evolution use comprehensive multilevel approach (Ivanova and Rozov, 1958).

The studies are based on the comparative geographic method of a complex multilevel study of soil genetic profiles in the natural evolutionary conjugate and agrogenic series of chernozems in the center of the Russian Plain.

The basis of the methodological approach to studying the evolution of chernozems were the following principles: 1) determination of the leading factor and the main process that determine the observed changes; 2) analysis of changes in the composition and properties of chernozems in the genetically conjugated zonal and agrogenic series; 3) analysis of the correspondence of the nature and direction of changes in properties, processes, and factors that determine them in the evolutionary genetic subtype and agrogenic (virgin land – arable land – irrigated arable land) series; 4) paired analysis of changes in direction of evolution of chernozems in the studied series.

The actual material was obtained by averaging large amounts of experimental data characterizing the profile distribution of the studied characters for each taxon. Data arrays were formed taking into account the features of type and intra-type variation of soil properties.

The study objects were the chernozems from the center of the Russian Plain, which includes the territories of 6 Russian regions: Kursk, Oryol, Lipetsk, Tambov, Belgorod, and Voronezh.

The studies were conducted on podzolized, leached, typical, ordinary, and, in part, on transitional to southern chernozems. The chernozems of only clay and heavy loamy particle-size composition were analyzed.

The natural evolution of soils was studied in the evolutionary genetic series of chernozems under natural vegetation in the reserved areas: Khripunskaya steppe, Kamennaya steppe, Streletskaya steppe, Khrenovskaya steppe, as well as in fallow areas of Kursk and Oryol regions. Only sections in undisturbed landscape-ecological conditions typical for chernozem formation were taken into consideration.

3. Results

Morphogenetic characteristics of soils. A detailed study of morphogenetic properties showed that soils of chernozem type under natural vegetation are characterized by a powerful, well-developed profile; intensely dark, almost black color, gradually weakening with depth; well-defined granular structure in most of the humus stratum; weakly compacted consistency, gradually increasing in the lower horizons, the absence of noticeable signs of eluvial-illuvial differentiation of the profile; the uneven, tongued border of the transition of the humus horizon into the parent rock; the presence of a carbonate horizon, usually confined to the lower boundary of the humus stratum and characterized by various forms of carbonate neoplasms. To the greatest extent, the noted typical features are expressed in the central subtype – typical chernozems, where, according to many researchers, the maximum intensity of the chernozem-forming process is observed (Aderikhin and Tikhova, 1963). The chernozems to the north of the typical chernozems have more signs characteristic of humid soil types; signs characteristic of arid soil types are more widespread in the south chernozems.

A significant transformation of morphological and morphogenetic properties is noted in arable chernozems. At the first stages of cultivation, these transformations are localized in the upper part of the soil stratum; at the subsequent stages, they spread deeper. Thus, modern agricultural use of chernozems results in the following:

1. The transformation of the humus profile, manifested in a change in color, power, content, and quality of humus;
2. Transformation of the carbonate profile, fixed in a change in its thickness, depth, forms of newly formed carbonates, the nature of migration processes;
3. Formation of anthropogenic neohorizons: compacted (“sole shoe”) in the lower part of the arable layer, texture-clayed in the subhumus part, and iron segregation zone in the lower part of the profile;
4. A change in the structural organization of the humus stratum of the profile, manifested in the deformation of the shapes, sizes, cuts of pedals, their packaging, intrapedal organization, etc.

5. Transformation of the soil mass consistency expressed in changes in the density of the soil and its solid phase, soil porosity, etc.

6. The appearance (especially in old arable chernozems) of dusty-clayey-humus film formations – a cutan on the edges of the pedals in the horizons AB and B.

The degree and nature of the manifestation of these phenomena increase depending on the duration and intensity of soil use in agricultural production. They are most clearly expressed in irrigated chernozems. At the same time, we admit that the listed morphogenetic changes of chernozems under anthropogenesis are not limited to the noted phenomena.

Physical and water-physical properties of chernozems and their change in genetically conjugated and agrogenic series. The soils with clay and heavy loam particle size distribution are most common in the Central Chernozem region (Akhtyrsev and Akhtyrsev, 1993). As is known, particles of silt and coarse dust prevail in the particle size fractions of these varieties – their share is about 70%. Chernozems are also composed of fine, medium dust, and fine sand fractions, in descending order. Coarse and medium sand account for the smallest share (Scherbakov, 2001). An increase in particle size distribution, accompanied by an increase in the content of silt, fine dust, and a decrease in the number of coarse dust particles is clearly traced in the genetically conjugated series from podzolized to ordinary chernozems. This results in a change in the ratio of two dominant fractions in this series: silt and coarse dust. Silt and coarse dust particles predominate in ordinary chernozems; in typical chernozems, the content of these fractions is leveled, while in leached and podzolized, on the contrary, prevail coarse dust. Inside, the profile distribution of these fractions is characterized by an increase in the proportion of silt and a relative decrease in the dust fraction from top to bottom. In the process of soil formation, these processes intensify from southern to northern subtypes and in the virgin – arable – irrigated chernozems series. Thus, in arable chernozems, the silt balance in relation to the parent rock shifts in the negative direction compared to virgin analogues (Table 1). In turn, dehydration, the maximum intensity of which is observed in arable horizons, is enhanced in the series from ordinary to podzolized chernozems.

In the structural-aggregate composition of virgin chernozems prevail monotypic aggregates of a granular form, which are characterized by high water resistance.

To the greatest extent, these features are manifested in typical and ordinary chernozems.

The use of chernozems in agricultural production leads to an increase in the share of aggregates over 10 mm, a decrease in the granular and dusty fractions, and a decrease in the water resistance of structural elements (Akhtyrsev and Lepilin, 1983; Berezin et al., 1983; Voronin et al., 1986; Rode, 1984; Mordhorst et al., 2012). These negative changes progressively increase with the use of chernozems in irrigated agriculture (Akhtyrsev and Lepilin, 1979; Bondarev, 1982; Scherbakov et al., 1988).

The study of the hydrological regime showed that in virgin chernozems, the greatest amount of moisture, as a rule, is noted in the spring after snowmelt. During the growing season, virgin vegetation expends moisture mainly from the upper meter layer, where the greatest seasonal changes in humidity are observed (Orlov, 1985; Scherbakov, 2001).

In arable chernozems, the water regime is different. In the first half of the growing season, the change in humidity in arable chernozems is quite close to that in chernozems under natural vegetation. Differences are observed in the second half of summer. During this period, on the virgin soil, the vegetation continues to grow and, therefore, to expend moisture, while on the arable land, the desuctive expenditure of moisture ceases after harvesting, and it is deleted from the soil only as a result of physical evaporation. The "underutilization" of moisture at the end of summer, as well as its lower expenditure by cultivated vegetation during the growing season, determine the annual increase in moisture compared to the steppe by an average of 20–40 mm with an oscillation ranging from 10 mm to 140 mm (Orlov, 1985). The annual underutilization of moisture leads to an increase in the depth of spring moistening and more frequent, than on virgin soil, end-to-end wetting of the soil profile. That is, although the water regime of arable typical chernozems remains periodical irrigation, in quantitative terms it shifts in a more humid direction.

Under irrigation conditions, the water regime is characterized by a more frequent and deeper, compared with non-irrigation cases, soaking of the soil-earthcover. The average annual increase in moisture under these conditions is 50–80 mm. All this allows stating that during irrigation the water regime of chernozems shifts by more than one subtype gradation in the humid direction.

Physical and chemical properties of chernozems and their change in genetically conjugated and hydrogenated series. In virgin chernozems, the cation exchange capacity (CEC) in the upper horizons averages 55 mmol (equiv)/100 g. In a genetically conjugated series of virgin chernozems, a regular increase in CEC ranges from 38 mmol (equiv)/100 g in podzolized chernozems to 55 mmol (equiv)/100 g in ordinary chernozems that is due to corresponding changes in the content of organic matter and silt fraction (Aderikhin and Tikhova, 1963). The degree of saturation with bases, as a rule, exceeds 90%. The largest share of exchangeable cations accounts for calcium (up to 80%); the proportion of magnesium averages 15% (Table 2). Absorbed H^+ accounts for a small share of the cations, while exchangeable Na^+ accounts for a small share of the southern subtypes. In the composition of the exchangeable cations of soils from podzolized to ordinary chernozems, we registered regular increase in the amount of exchangeable Ca^{2+} and Mg^{2+} and slight increase in the amount of exchangeable Na^+ with a decrease in the content of absorbed H^+ . Among the studied subtypes, the largest proportion of calcium and the smallest proportion of magnesium are observed in typical chernozems. To the north and south of them, the percentage of calcium in SAC composition decreases markedly, while the proportion of magnesium increases. The indicated changes in the ratio of the exchangeable cations of calcium and

magnesium is due to the difference in the solubility of their salts, the strength of the bond with SAC, as well as to the change in the water regime of soils (Orlov and Biryukova, 1984; Samoylova et al., 1987; Samoylova et al., 1991).

Plowing of virgin chernozems is accompanied by a noticeable transformation of SAC. First of all, we noted a 5–9% decrease of CEC in arable chernozems, a decrease in the content of exchangeable Ca^{2+} and Mg^{2+} by 4–9% and 20–30%, respectively. In most subtypes, the indicated changes occur mainly in the arable horizon, with the exception of podzolized chernozem, in which changes in the SAC are observed throughout the humus mass.

Along with this, in the SAC of arable chernozems, we observe an increase in the share of absorbed H^+ , which is recorded in cultivated soils, in the deeper layers of the profile compared to virgin differences (Table 2). In the series of subtypes under consideration, the greatest Ca^{2+} losses are recorded in podzolized chernozems (approximately 9%) and somewhat less in ordinary chernozems (up to 4%). The amount of exchangeable Mg^{2+} , on the contrary, decreases to a greater extent in ordinary chernozems (up to 30%) and to a lesser extent in podzolized ones (up to 20%). At the same time, the content of absorbed H^+ increases as much as possible in podzolized chernozems and not so much in ordinary chernozems. In arable chernozems, especially in the upper horizons, the ratio of Ca^{2+} to Mg^{2+} increases to 6:1; 7:1 versus 5:1 for virgin differences, due to the displacement of exchangeable magnesium by hydrogen during acidification of the soil (Orlov and Biryukova, 1984; Ponizovsky et al., 2001).

Irrigation of chernozems even with fresh waters (0.2–0.5 g/L) of sulfate-bicarbonate-calcium-magnesium composition has a powerful effect on the state of the SAC of chernozems. During irrigation, there is a decrease in the capacity of cation exchange in the upper layers of the soil and some increase in the underlying layer. In the composition of the SAC, the Ca^{2+} content decreases while the content of Mg^{2+} , Na^+ , and H^+ increases. In accordance with this, the degree of unsaturation of SAC with bases is growing. SAC composition also changes in terms of the cation ratio. These changes are unidirectional and similar to those noted in the evolutionary-genetic series from ordinary to podzolized subtypes of virgin chernozems during the humidization of the water regime.

Carbonate profile of chernozems, its features, and the nature of evolution. An analysis of the data shows that, in general, the carbonate profile of chernozems can be conditionally divided into three horizons, characterized by certain gradients of changes in carbonate content and variational-statistical indicators. The upper horizon (leaching) is characterized by absolute minimum content of carbonates and gradient of its change with depth, as well as a weakly uniform, accumulative type of distribution. By the nature of the spatial variability of the trait, this part of the profile, in turn, is divided into two subhorizons: the uppermost layer – frontal leaching and the lower subhorizon — pulsation and migration processes (Afanasyeva, 1966) with the highest values of variation coefficients in the carbonate

content. The horizon of intense illumination of CaCO_3 lying below is characterized by a maximum gradient of variation in its content with depth and a relatively high coefficient of variation of this indicator. The lowest carbonated strata (Mikhailova and Post, 2006a, 2006b; Khokhlova et al., 2020) is characterized by a high content of carbonates and a minimum value of variation of the considered indicator, i.e. with a conservative state of the trait (Figure 1).

The zonal series of chernozems preserved the considered typical structural features of the carbonate profile, but its morphogenetic parameters change significantly. In virgin chernozems, the moisture content increases from ordinary subtypes to podzolized soils. The carbonate profile shows, firstly, an increase in the thickness of the leaching horizon, and within the latter, an increase in the upper subhorizon, a decrease in the thickness of the subhorizon and in pulsation-migration processes; secondly, a decrease in the thickness of the transition horizon and, accordingly, sharpening the boundary of the transition to the carbonate stratum; and, finally, an increase in the gradient of changes in the concentration of carbonates with depth in the series of chernozems under consideration.

In general terms, adequate changes in the carbonate profile are observed in the series virgin land – arable land – irrigated arable land. In particular, plowing of chernozems leads to increased mobility and a decrease in the amount of carbonates in the soil profile. At the same time, migration processes reach the highest intensity in the southern subtypes that is due to the proximity of the carbonate horizon to the surface and, accordingly, the frequency of its “capture” by descending-ascending currents of soil moisture. The latter circumstance often leads to a temporary increase in the boiling line and, accordingly, to alkalization of the soil medium in these subtypes of chernozems. In the northern subtypes, the corresponding soaking of the carbonate stratum in most cases coincides with the periodic soaking of the soil profile as a whole. This leads to a unidirectional increase in the removal of carbonates beyond the soil profile and, as a result, acidification of the soil medium.

In irrigated chernozems, the seasonal dynamics of pulsation-migration processes is characterized by a greater amplitude and frequency of oscillations that in the first stages of irrigation often leads to alkalization of the upper horizons of the southern subtypes. Irrigation of the northern subtypes is accompanied by unidirectional acidification of the soil. In general, under irrigation conditions, the leaching zone expands, the carbonate content decreases over the entire profile, the boiling line drops, the coefficient of variation in the carbonate content in the horizon of pulsation-migration processes reaches a maximum and its lower boundary lowers, and the coefficient of variation in the upper part of the carbonate strata slightly increases (Scherbakov, 2001).

The foregoing allows concluding that the distribution of carbonates in the profile of chernozems is the result of soil formation processes. Quantitative differences in the content of free carbonates and unidirectional morphogenetic changes in the carbonate profile of the considered soil series

unambiguously testify to the genetical relationship of the latter with the hydrothermal regime of soils and indicate its evolutionary direction towards neighboring, more humid subtypes.

Humus profile of chernozems and the direction of its evolution. Statistical analysis of a large number of humus profiles showed that in virgin chernozems in the studied region the distribution of organic matter as a whole is characterized by a uniformly accumulative type (Samoylova et al., 1987; Mikhailova and Post, 2005; Zhang et al., 2001). However, a detailed analysis of the distribution curve indicates that within the profile the type of distribution of humus is not the same – in the upper part (city A) it is regressively accumulative; in the middle part, it is uniformly accumulative; and in the bottom part, it is again regressive-accumulative. The gradient of the drop in the humus content in various parts of the profile changes in accordance with this distribution. In the upper layers, its value is maximal; in the lower layers, it is minimal (Table 3). The noted differences suggest that the processes of humus formation and humus accumulation are inadequate; they also allow making some conclusions on their role in various parts of the soil stratum.

The noted features of the humus profiles of chernozems are quite well manifested in a genetically conjugated series of subtypes. Each subtype is characterized by characteristic drop gradient in the humus content or regression coefficient, which naturally increases from 0.064 in podzolized to 0.083 in ordinary chernozems. With increasing humidity, the type of distribution curve changes from uniformly accumulative in ordinary chernozems to eluvial-illuvial in podzolized chernozems (Figure 2). These changes occur against the background of unidirectional amplification of the factor causing the redistribution of organic substances in soils, i.e. water regime. Other known factors that determine the formation of the humus profile, namely, biological productivity, distribution of root systems, period of biological activity (Ramazanov, 1977), and others do not reveal such an unambiguous relationship that could explain the nature of the change in humus profiles in the considered series of soils.

The plowing of virgin chernozems leads to a significant decrease in the humus content in arable chernozems (Volkov et al., 2019; Bryk and Kołodziej, 2014). At the same time, we register inadequacy of humus losses in various subtypes and parts of the soil profile.

In ordinary chernozems, a decrease in humus is observed throughout the soil profile. In typical chernozems, it decreases significantly in the upper and lower parts of the humus layer and slightly increases as a result of redistribution in the middle part that generally leads to the appearance of signs of eluvial-illuvial differentiation of the humus profile in these chernozems, bringing them closer in the form of the profile distribution of humus to virgin leached differences.

In leached arable chernozems, as in ordinary arable lands, a decrease in humus is observed throughout the profile, but there is an increase in signs of illumination of humus in the horizon B and an increase in the intensity of a decrease in the reserves of organic substances in the lowest part of the humus and subhumus strata. As a result, the differentiation of the soil profile into eluvial and illuvial

parts is intensified in leached arable chernozems whereas the humus profile is shortened, i.e. we register the signs observed by us earlier in virgin podzolized chernozems.

Podzolized chernozems under agricultural use undergo the greatest changes (Figure3).

In this subtype, we registered the maximum losses of humus throughout the layer. In general terms, the humus distribution curve becomes wave-like. Based on the gradient of the fall in the content, a more intensive removal is observed in the subsurface horizon and in the lower part of the humus profile, which, ultimately, leads to a shortening of the humus profile as a whole and intensification of the signs of the eluvial horizon in its middle part.

The involvement of chernozem soils in irrigated agriculture is accompanied by an intensification of their dehumification. Thus, if for more than 200 years of use, the amount of humus in the upper horizon of the non-irrigated arable soils decreased by 1.5–2.0% (Aderikhin and Tikhova, 1963), during approximately 10 times shorter irrigation period the loss of humus in the corresponding layer was approximately 1.0%. In the profile distribution of organic matter, the drop gradient of its content decreases from 0.056 in rainfed soils to 0.048 in irrigated soils. Moreover, the organoprofile of irrigated soils undergo the observed transformations due to a change in one factor – the water regime. Comparing the data obtained, we can conclude that the evolution of the humus profile of arable chernozems in the series virgin land – arable land – irrigated arable land is similar to that in the series from ordinary to podzolized subtypes of virgin analogues.

4. Conclusion

Analysis of the current state of chernozems in central Russia and the characteristics of changes in their properties in the genetically conjugated and agrogenic series showed a significant transformation of their morphological, morphogenetic, physical, water-physical, chemical, and physicochemical properties. All the changes are patterned and in most cases are similar in the considered series: these processes intensify with the transition from southern to northern subtypes in genetically conjugated series and in the agrogenic series virgin – arable lands– irrigated chernozems. Along with this, it was established that in the process of soil formation in chernozems, particle size distribution fractions are redistributed inside the profile. The intensity of this process increases with the transition from southern to northern subtypes and in the series virgin chernozems – arable chernozems– irrigated chernozems. An analysis of the physical and water-physical properties of virgin and arable chernozems showed a correlative relationship between the humidization of the water regime of soils and the deterioration of the physical properties of chernozems.

Plowing of virgin chernozems is accompanied by a noticeable transformation of SAC. These changes are also unidirectional and similar to those noted in the evolutionary-genetic series from ordinary to podzolized subtypes of virgin chernozems during humidization of the water regime.

The distribution of carbonates in the chernozem profiles is the result of soil-forming processes. Quantitative differences in the content of free carbonates and morphogenetic changes of the carbonate profile in the considered soil series unambiguously testify to the genetical relationship of the latter with the hydrothermal regime of soils and indicate its evolutionary direction towards neighboring, more humid subtypes.

The evolution of the humus profile of arable chernozems in the series virgin land – arable land – irrigated arable land is similar to that in the series from ordinary to podzolized subtypes of virgin analogues.

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Table 1. Claying coefficient and silt balance in virgin and arable chernozems

Depth, cm	Chernozem subtype							
	Podzolized		Leached		Typical		Ordinary	
	R _c *	Balance	R _c	Balance	R _c	Balance	R _c	Balance
Virgin chernozems								
0–10	0.79	-17.1	0.85	-25.8	0.90	-17.7	0.92	-12.5
20–30	0.84	-14.4	0.91	-13.5	0.90	-15.4	0.92	-11.3
40–50	0.96	-0.3	0.97	-23.6	0.92	-12.2	0.96	-7.4
60–70	1.00	+6.5	1.05	-6.5	0.94	-9.4	0.97	-6.5
80–90	1,03	+9.2	1.00	-11.8	0.96	-8.7	0.99	+1.9
100–110	1.10	+14.7	1,03	+5.9	1.01	+1.5	0.98	-0.7
120–130	1,02	+11.3	1,02	+2.5	0.95	-4.7	0.99	+1.2
140–150	1.00	-	1.00	-	1.00	-	1.00	-
Arable chernozems								
0–10	0.86	-30.4	0.82	-29.0	0.86	-25.4	0.85	-20.0
20–30	0.81	-22.8	0.83	-23.5	0.93	-20.7	0.85	-18.5
40–50	0.90	-23.7	0.90	-18.5	0.90	-19.5	0.90	-10.0
60–70	0.92	-12.5	0.87	-19.5	0.97	-10.4	0.86	-14.5

80–90	0.94	-11.2	0.93	-13.0	0.92	-13.4	0.93	-5.8
100–110	0.94	-8.4	0.95	-11.7	0.95	-9.7	0.96	+1.5
120–130	0.98	-7.6	0.95	-10.7	0.98	-4.0	0.97	+4.2
140–150	1.00	-	0.95	-12.7	0.97	-3.5	0.92	-6.2
190–200	-	-	1.00	-	1.00	-	1.00	-

R_c – coefficient of claying

Note. Decrease (-) or increase (+) in silt is expressed in relative percentages of its content in the rock

Table 2. The content of exchangeable cations in typical chernozems in different lands (average data).

Depth, cm	Exchangeable cations, mmol (equiv)/100 g of soil							
	Ca ²⁺	Mg ²⁺	Na ⁺	H ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	H ⁺
	<u>Virgin soil (n=33)</u>				<u>Arable land (n=196)</u>			
0–10	39.9	7.4	traces	3.1	38.0	5.4	0.2	3.3
10–20	38.5	6.1	-	2.5	35.6	5.0	0.2	3.0
20–30	36.7	5.9	-	2.0	35.7	5.0	0.2	2.9
30–40	34.3	5.5	-	1.8	33.5	4.8	0.2	2.1
40–50	32.0	5.0	-	1.2	32.8	4.7	0.2	1.8
50–60	29.5	4.8	-	0.8	30.7	4.3	0.2	1.4
60–70	28.2	4.8	-	0.6	30.4	4.4	0.1	1.1
70–80	27.9	4.6	-	0	27.1	4.3	0.2	0.6
80–90	24.7	4.1	-	0	26.4	4.2	0.1	0
90–100	23.8	4.2	-	0	25.4	4.2	0.1	0
	<u>Arable land irrigated for 5 years (n=60)</u>				<u>Arable land irrigated for 13 years (n=60)</u>			
0–10	36.1	3.1	0.6	3.0	34.4	4.9	0.5	3.3
10–20	35.4	3.0	0.6	3.2	34.0	5.1	0.4	3.4
20–30	34.8	2.9	0.5	3.0	33.5	5.1	0.4	3.0
30–40	33.7	2.7	0.4	1.9	33.1	4.6	0.4	2.1

40–50	32.4	2.7	0.3	1.4	32.7	4.2	0.4	1.6
50–60	31.5	2.7	0.3	1.1	31.9	3.9	0.4	1.4
60–70	30.3	2.3	0.4	0.8	29.9	4.1	0.3	1.0
70–80	28.1	2.4	0.2	0.5	28.4	4.1	0.4	0.7
80–90	26.1	2.3	Traces	0	27.2	3.8	0.4	0.6
90–100	25.1	2.5	-	0	26.4	3.7	0.4	0

Table 3. Average typical indicators of the content and distribution of humus in the profile of virgin chernozems, % (n=96).

Depth, cm	– X	Boundary values		R	Depth, cm	– X	Boundary values		R
		max	min				max	min	
0–5	10.7	12.9	8.1	-	100–110	1.2	2.2	0.5	0.6
0–10	8.5	12.1	6.8	4.4	110–120	1.0	2.1	0.5	0.2
10–20	7.2	11.9	5.7	1.3	120–130	0.8	2.1	0.6	0.2
20–30	6.5	9.4	5.4	0.7	130–140	0.8	2.0	0.6	0.0
30–40	5.4	6.7	4.5	1.1	140–150	0.7	1.8	0.5	0.1
40–50	4.7	6.0	3.3	0.7	150–160	0.6	1.3	0.4	0.1
50–60	4.1	5.2	3.0	0.6	160–170	0.6	0.9	0.3	0.0
60–70	3.5	4.8	1.3	0.6	170–180	0.6	0.6	0.2	0.0
70–80	2.9	4.0	1.0	0.6	180–190	0.6	0.6	0.2	0.0
80–90	2.2	3.3	0.7	0.7	190–200	0.6	0.6	0.2	0.0
90–100	1.8	2.6	0.7	0.4	-	-	-	-	-

Note: X – weighted average; max, min – the maximal and minimal values of the trait; R – humus decrease gradient, in %/dm.

Figure 1 Diagram of the structure of the carbonate profile of chernozems

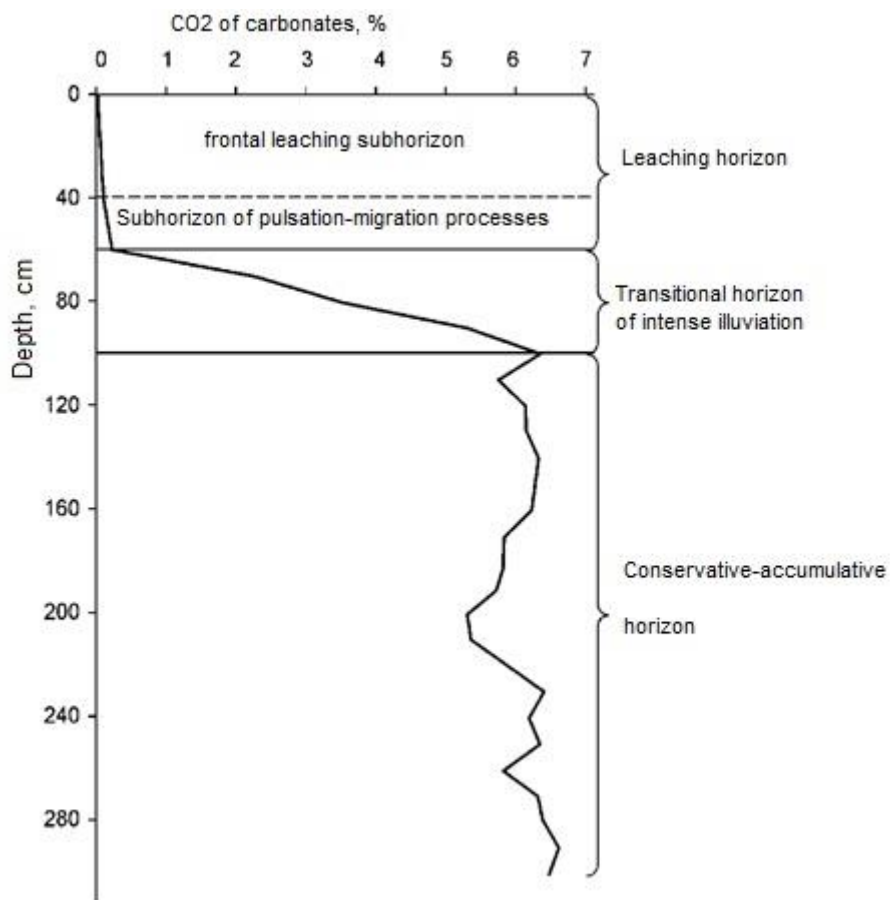


Figure 2 Profile distribution, equations, and regression lines of humus in various subtypes of virgin chernozems: 1–podzolized; 2–leached; 3–typical; 4–ordinary.

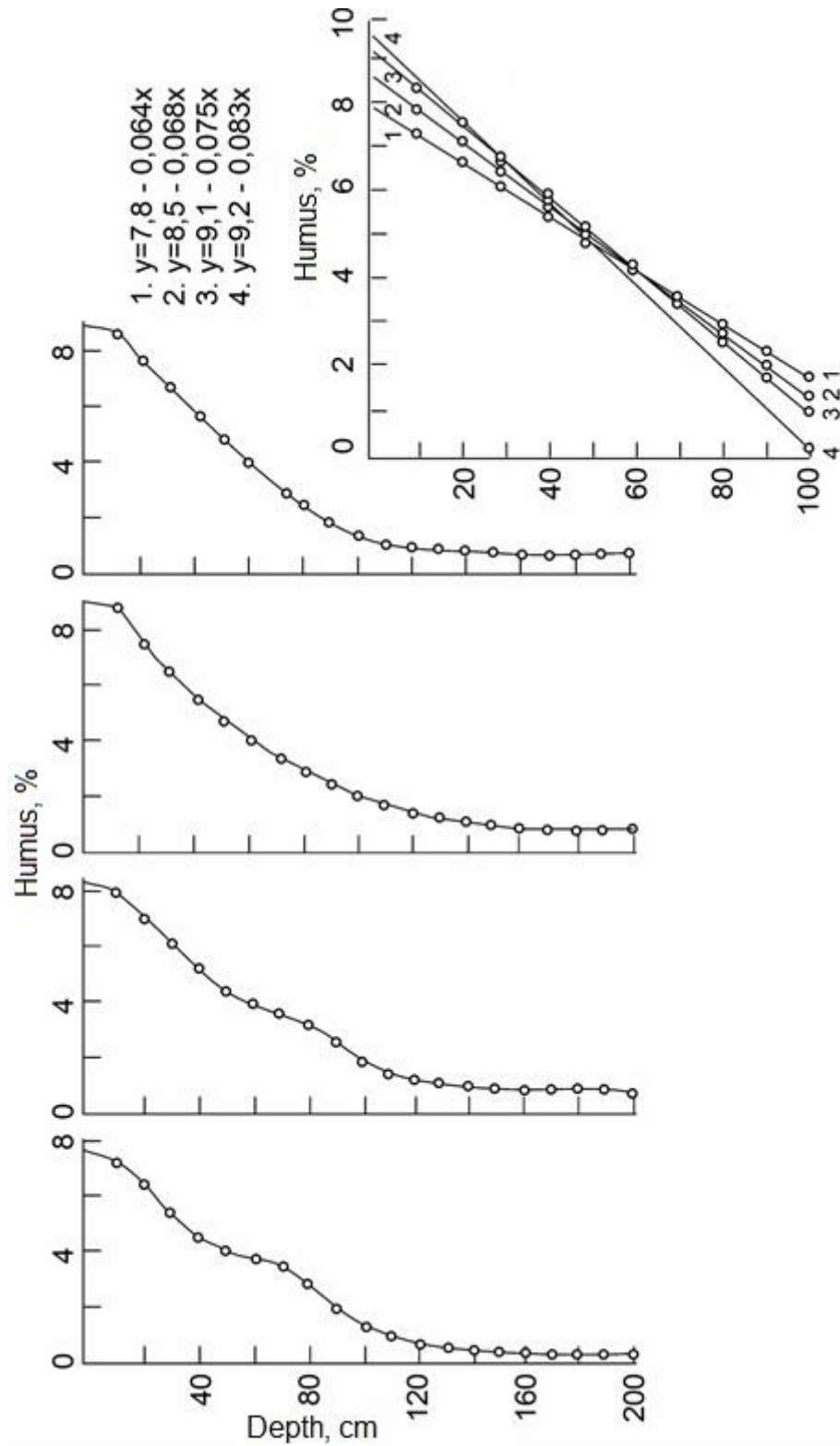


Figure 3 Profile distribution, equations, and regression lines of humus in virgin and arable podzolized chernozems

