Anthropogenic Evolution of Dark Gray Forest-Steppe Soils in the Southern Part of the Central Russian Upland

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Abstract—A sequence of dark gray forest soils developing under a virgin broadleaved forest and under croplands used for 100 and 150 years was studied in the southern part of the forest-steppe zone on the Central Russian Upland. The application of multiple study methods for these objects made it possible to trace the evolutionary changes in the soil properties during the 150-year-long period of regular plowing. Several important trends in the soil development under the impact of the cultivation were revealed: (a) an increase in the thickness of the humus layer (according to the measurements at 20 points for each of the objects), (b) an increase in the amount of mole tunnels, (c) a decrease in the coefficient of the textural differentiation of the soil profile (with respect to the clay content), (d) an increase in the contents and reserves of the major nutrients upon a stable pool of humus in the upper meter, and (e) some alkalization and carbonization of the profile. Powdery accumulations of carbonates and whitish calcareous coatings on the faces of prismatic peds appeared at a depth of more than 130 cm. The plowed soils contained thin deep fissures, the surface of which was covered by dark-colored clayey-humus coatings at the depth of 50–110 cm. The radiocarbon age of the humus in these coatings was 500–1000 years younger than the age of the humus in the soil mass between the fissures. This set of features attests to the evolution of the plowed dark gray forest soils into chernozems under the impact of plowing.

INTRODUCTION

The agrogenic impact on soils is one of the most powerful factors changing the chemical, physical, and morphological properties of plowed soils at all the levels of the soil profile organization. These changes characterize the soil evolution proceeding at a very high rate. It should be noted that the idea of the high intensity of agrogenic changes in the soil profiles is one of the debatable problems. Not all the researchers agree with this opinion. In particular, different opinions about the intensity and direction of the agrogenic evolution of gray forest soils in the forest-steppe zone may be found in literature [1, 3, 4, 6, 10, 12, 15, 16, 19]. The depth, intensity, stages, and particular mechanisms of soil changes under the impact of rainfed farming have yet to be studied.

The direction of the temporal changes in the properties of gray forest soils under the impact of plowing is also open to argument [6, 15, 16, 19, 20]. New experimental data are needed to find well-grounded answers to the disputable problems. The results of special investigations into the evolution of gray forest soils under the impact of plowing within the forest-steppe zone of the Central Russian Upland are discussed in this paper.

OBJECTS AND METHODS

The Polyana key site is found in the Shebekino district of Belgorod oblast. This territory belongs to the southern part of the Central Russian Upland and represents a slightly inclined (up to 2°) interfluve between the Severskii Donets and Koren rivers. Up to the beginning of the intensive land development in the 17th–18th centuries, the studied interfluve was covered by broadleaved oak forests.

The analysis of the history of the land use in this area showed that soils were tilled with a wooden plow to a depth of 15–20 cm up to the 1930s; then, mechanical plowing with the use of tractors began. The depth of the plow layer gradually increased. At present, it is about 30–37 cm. The application of mineral and organic fertilizers began after World War II. The rates of the fertilization have been relatively low. Thus, the annual input of farmyard manure has never been higher than 4 t/ha. The Polyana key site includes the following plots: a virgin broadleaved forest, a

100-year-old cropland, and a 150-year-old cropland. During the entire period of the existence of these croplands, they have not been subjected to overgrowing with trees or other natural cenoses. Their development in the second part of the 19th century and at the beginning of the 20th century was related to the high density of the population in the former Kursk gubernia and the absence of free land plots. In that period, not only the interfluvial plains but also the slopes of local ravines and river valleys were plowed up. At the beginning of the 20th century, the percentage of cultivated areas in this region was very high [7, 11].

The studied plots occupy similar geomorphic positions (flat interfluves) and have similar lithologies (loess-like calcareous clay). On each of the plots, two full-profile soil pits located at about 10 m from one another were examined.

Our study can be referred to as a study of the chronosequences of the agrogenic soils (agrochronosequences). This method is based on the comparative analysis of the morphology and properties of the soils on the background plots with natural vegetation (indicating the zero-moment of the agrogenic pedogenesis) and on the arable fields of different ages located in the same positions of the relief and developing from the same parent materials. In this context, in the course of the selection of the key plots, preferences were given to the areas where croplands of different ages and plots with virgin broadleaved forests are found close to one another and occupy similar geomorphic positions. Such plots were identified on the basis of the analysis of large-scale cartographic materials developed in different years, including the General Land Use Planning Scheme (developed at the end of the 18th century) and the Special Land Use Planning Scheme of the Russian Empire developed in the middle of the 19th century.

The laboratory studies included the radiocarbon dating of the soil humus and carbonates (in the Radiocarbon Laboratory in Kiev); the micromorphological description of the soil carbonates; and analyses of the physical, physicochemical, and chemical soil properties by routine methods.

RESULTS AND DISCUSSION

The forest plot represents a lime–maple stand with an admixture of oak and ash trees. Under the tree canopy, forest herbs with a predominance of Aegopodium, Geum, and Asarum are developed. The soil profile includes the following horizons: A1–A1A2–A1A2Bth–A2Bt–Bt1–Bt2–BtC_{Ca}–BC_{Ca}. The thickness of the A1 horizon reaches 17 cm, and the total thickness of the humus layer (A1–A1A2Bth) is 42 cm. The zone of podzolization is diagnosed by the presence of whitish skeletans in the layer of 17–42 cm; these pedofeatures are superimposed over the soil humus profile. The illuvial part of the profile is brown-colored; it has a heavier texture and an angular blocky structure with illuviation coatings on ped faces. In the lower part of the illuvial layer (in the BtC_{Ca} horizon), the illuviation processes responsible for the formation of brown organomineral coatings are combined with the accumulation of calcareous pseudomycelium. The depth of the effervescence is 126 cm. Ancient mole tunnels of grayish brown color with diffuse boundaries are present in the lower part of the soil profile. Their development attests to the former steppe stage of the pedogenesis that preceded the Late Holocene stage of the forest pedogenesis [2, 20]. According to its morphogenetic features, this soil profile belongs to the subtype of gray forest soils.

The soil pits under the 100-year-old cropland were dug at a distance of 110 m from the pits characterizing the background forest soil and 30 m from the forest border. The plowed soil of this plot has the following horizonation: Ap–A1A2Bth–A2Bt–Bt1g–Bt2g–BtC_{Ca}–BC_{Ca}. The plow horizon was formed due to the mixing of the initial A1; A1A2; and, partly A1A2Bth horizons of the virgin soil. The degradation of the soil's structure, some compaction of the upper horizons, and the wetting–drying cycles in the plowed soil resulted in the development of thin (0.5–1.0 cm) vertical fissures that serve as migration pathways for humified suspensions penetrating to the depth of 100–110 cm from the upper part of the profile. This process is marked by the appearance of thin humus coatings on the walls of the fissures in the lower part of the Bt2g horizon. The illuvial horizons of the plowed soil are unevenly colored; zones of weak gleyzation with an olive-brown color are distinguished in them. The development of gley processes in the plowed soil is also seen from the increase in the number and sizes of the Fe–Mn concentrations. The thickness of the eluvial layer in the plowed soil is smaller than that in the background forest soil owing to the appearance of the plow horizon. At the same time, the arrangement of whitish skeletans in the eluvial layer of the plowed soil has changed. Most of them are allocated to the zones around the deep vertical fissures. It is probable that more active water infiltration through these fissures has enhanced the downward migration of suspensions from the upper horizons into the lower horizons. The presence of recent mole tunnels in the upper part of the profile of the plowed soil should also be noted. Such mole tunnels differ from the old mole tunnels found in the forest soil: they are filled with a relatively loose soil material, and their outer boundaries are very distinct. Certain changes have taken place in the soil's carbonate profile. Abundant calcareous pseudomycelium of whitish yellow color are seen in the BC_{Ca} horizon of the plowed soil. Powdery concentrations of carbonates covering the faces of prismatic peds are seen in the zones of deep fissures. They form a lattice-like pattern on vertical and horizontal sections of the soil within the upper part of the calcareous horizons (in the BtC_{Ca} horizon).

Table 1. The depths of the lower boundaries of the genetic horizons and the depth of the effervescence in the studied soil profiles, cm (the mean data from 20 measurements at each of the plots)

Soil								
forest			cropland, 100 yrs			cropland, 150 yrs		
horizon	$X \pm \delta_X$	δ	horizon	$X \pm \delta_X$	δ	horizon	$X \pm \delta_X$	δ
A1	16.73 ± 0.44	2.05	Ap	34.18 ± 0.60	2.81	Ap	36.68 ± 0.32	1.49
A1A2	27.68 ± 0.49	2.30						
A1A2Bth	41.82 ± 0.50	2.36	A1A2Bth	44.50 ± 0.99	4.63	A1	49.23 ± 0.79	3.72
A2Bt	58.50 ± 0.58	2.72	A2Bt	55.59 ± 1.00	4.67	A1At	63.09 ± 1.27	5.97
Bt1	84.27 ± 0.72	3.38	Bt1g	74.82 ± 1.07	5.01	At1	93.73 ± 1.56	7.32
Bt2	119.18 ± 0.83	3.90	Bt2g	108.82 ± 1.09	5.11	At2	127.00 ± 0.84	3.95
BtC_{Ca}	142.14 ± 0.96	4.49	BtC_{Ca}	135.23 ± 1.06	4.98	AtC_{Ca}	150.23 ± 0.90	4.20
Effervescence	126.18 ± 0.67	3.13	Effervescence	113.45 ± 1.38	6.47	Effervescence	126.81 ± 0.63	2.95

Table 2. Distribution of the bulk density (g/cm^3), clay content (%), and clay reserves (t/ha) in the studied soil profiles

Depth, cm	Soil								
	forest			cropland, 100 yrs			cropland, 150 yrs		
	bulk density	clay (<0.001 mm)		bulk density	clay (<0.001 mm)		bulk density	clay (<0.001 mm)	
		content	reserves		content	reserves		content	reserves
0–20	1.03	24	494	1.36	31	843	1.33	30	798
20–40	1.24	36	893	1.40	37	1036	1.31	33	865
40–60	1.46	38	1110	1.46	46	1343	1.29	42	1084
60–80	1.52	39	1186	1.50	46	1380	1.35	44	1188
80–100	1.49	39	1162	1.50	43	1290	1.43	45	1287
100–120	1.42	39	1108	1.48	43	1273	1.43	45	1287

According to its morphogenetic features, the soil of the 100-year-old cropland can be classified as an arable surface-gleyed dark gray soil.

At a distance of 150 m to the northeast from this plot, the soil of an older (150 years) cropland was studied. It has the following horizonation: Ap–A1–A1Bt–Bt1–Bt2–BtC_{Ca}–BC_{Ca}. The thickness of the humus layer in this old-arable soil has increased, and the zone with whitish skeletans has reduced. The amount of recent mole tunnels in this soil is higher than that in the soil of the 100-year-old cropland. According to its morphogenetic features, this soil can be classified as a medium-deep slightly podzolized chernozem.

The spatial–temporal changes in the morphometric characteristics of the soils in the studied agrochronosequence are summarized in Table 1. The differences between the soil profiles may be interpreted as an integral result of the temporal changes in the bulk density of the soil horizons (e.g., the compaction of the Ap horizon (Table 2) has led to the contraction of the soil in the vertical direction by 7 cm) and in the character of the soil processes during the agrogenic

Table 3. Some physical and water-physical properties of the studied soils

Horizon	Depth, cm	Aggregate-size distribution						Particle-size distribution		
		dry sifting			wet sifting					
		val. agr.	not val. agr.	K_{str}	aggregate size classes (mm) and their contents, %		K_{wst}	>0.01 mm	<0.01 mm	clay
		%			>5	<0.25		%		
Background soil (forest)										
A1+A1A2	3–21	88.4	11.6	7.6	5.2	16.4	0.85	53.0	47.0	22.6
A1A2Bth	21–47	88.9	11.1	8.0	3.0	12.3	0.90	44.0	56.0	36.4
A2Bt	47–65	55.8	44.2	1.3	0	36.3	0.64	38.9	61.1	37.9
Bt1+Bt2	65–102	31.7	68.3	0.5	0	30.7	0.70	39.9	60.1	39.8
BtC$_{Ca}$	102–120	27.6	72.4	0.4	0	51.9	0.49	37.6	62.4	38.0
BC$_{Ca}$	120–155	29.5	70.5	0.4	0.8	19.7	0.82	36.8	63.2	45.4
Cropland, 100 yrs										
Ap'	0–20	58	42	1.4	6.3	29.6	0.72	39.4	60.6	31.3
Ap"	20–33	33	67	0.5	2.3	16.1	0.80	38.5	61.5	34.2
A1A2Bth	33–43	28	72	0.4	0.5	54.3	0.84	34.2	65.8	43.9
A2Bt	43–65	16.3	83.7	0.2	0	16.1	0.84	34.8	65.2	45.7
Bt1g	65–90	16.2	83.8	0.2	0	27.2	0.73	32.4	67.6	44.9
Bt2g	90–110	14.6	85.4	0.2	0	33.3	0.67	35.0	65.0	43.7
BtC$_{Ca}$	110–130	13.1	86.9	0.2	0	32.6	0.68	32.9	67.1	43.5
Cropland, 150 yrs										
Ap	0–28	49.9	50.1	1.0	0.4	25.5	0.76	47.3	52.7	30.5
A1	28–48	53.2	46.8	1.1	2.0	25.4	0.76	38.4	61.6	36.3
A1Bt	48–60	49.1	50.9	1.0	0	19.7	0.81	32.2	66.8	43.6
Bt1	60–80	23.5	76.5	0.3	0	22.4	0.78	36.4	63.6	43.2
Bt2	80–100	18.6	81.4	0.2	0	22.9	0.78	35.3	64.7	44.4
BtCg$_{Ca}$	100–130	15.1	84.9	0.2	0	29.9	0.70	33.6	66.4	45.2

Note: (val. agr.) is the content of agronomically valuable aggregates (1–10 mm), (not val. agr.) is the total content of aggregates <1 mm and >10 mm, K_{str} is the coefficient of the structuring, and K_{wst} is the coefficient of the water stability of the aggregates.

stage of its development. The latter is clearly seen from the comparison of the soils under the 100-year-old and 150-year-old croplands. Some spatial variability in the particle-size distribution (Tables 2 and 3) should also be noted. This phenomenon could affect the differences in the initial morphogenetic properties of the compared soils. In the studied agrochronosequence (the background forest soil-the soil of the 100-year-old cropland-the soil of the 150-year-old cropland), the reserves of the clay (<0.001 mm) fraction in the layer of 0–42 cm of the background soil (from which the plow horizon was formed) and in the layer of 0–35 cm of the plowed soils (taking into account the compaction of the topsoil and its contraction by 7 cm) constitute 1500, 1570, and 1430 t/ha, respectively. The reserves of the clay fraction in the 1-m-deep layer of

Table 4. Radiocarbon ages of the studied soils

Horizon; depth, cm	Object of the dating	Laboratory no.	Age, yrs (noncalibrated)
		Background forest soil	
A1, 15–27	SM	Ki-13876	1920 ± 70
A1A2, 33–43	SM	Ki-13877	3970 ± 80
Bt1–Bt2, 70–90	OMC	Ki-13878	4520 ± 120
Bt2, 91–107	SM	Ki-14152	5790 ± 90
BtC_{Ca}, 127–135	PMT	Ki-14154	6380 ± 90
BC_{Ca}, 180–190	CC	Ki-14153	8690 ± 100
BC_{Ca}, 190–200	CC	Ki-16057	8240 ± 100
		100-year-old cropland	
Ap, 18–23	SM	Ki-13879	1430 ± 50
A1A2Bth, 38–46	SM	Ki-13880	5080 ± 60
Bt2, 90–96	RMT	Ki-13881	6030 ± 80
Bt2, 94–100	SM	Ki-14155	6420 ± 100
Bt2, 90–107	CHC	Ki-13882	5920 ± 130
BC_{Ca}, 165–175	CC	Ki-14159	8220 ± 80
BC_{Ca}, 200–210	CC	Ki-16046	8270 ± 150
		150-year-old cropland	
Ap, 18–29	SM	Ki-13883	1410 ± 60
A1, 42–52	SM	Ki-13884	4780 ± 70
A1Bt, 60–66	SM	Ki-14158	5280 ± 90
A1Bt, 62–66	PMT	Ki-13885	5670 ± 60
Bt2, 110–120	SM	Ki-14157	7100 ± 100
Bt2, 115–125	CHC	Ki-13886	6100 ± 120
BC_{Ca}, 162–167	RMT	Ki-13887	6240 ± 70
BC_{Ca}, 165–175	CC	Ki-14156	9070 ± 100
BC_{Ca}, 200–210	CC	Ki-16044	9150 ± 100

Note: SM—the soil mass, OMC—organomineral coatings of natural genesis, CHC—agrogenic clayey–humus coatings, CC—carbonate concentrations, PMT—paleomole tunnels filled with compact humified material, and RMT—recent mole tunnels filled with loose humified material.

these soils reach 4850, 5900, and 5200 t/ha, respectively. In the layer of 0–180 cm, they amount to 9700, 10850, and 9100 t/ha, respectively. This variability (with a variation coefficient of 5–10%) may be considered as the natural variability of the soil texture; it does not exceed the limits of the textural class of a light clayey soil developed from loess-like calcareous clay.

The radiocarbon dating of the soil samples (Table 4) showed that the organic matter from the clayey–humus coatings covering the walls of the deep fissures penetrating into the illuvial horizons is 500–1000 years younger than the organic matter (humus) in the soil mass between the fissures. This attests to the secondary character of the coatings and their enrichment in relatively young humic substances. Also, the organic matter from the recent mole tunnels (that appeared in the plowed soils) is somewhat younger than the organic matter in the surrounding soil mass, which may be explained by the penetration of humified material from the surface horizon into these tunnels (Table 4).

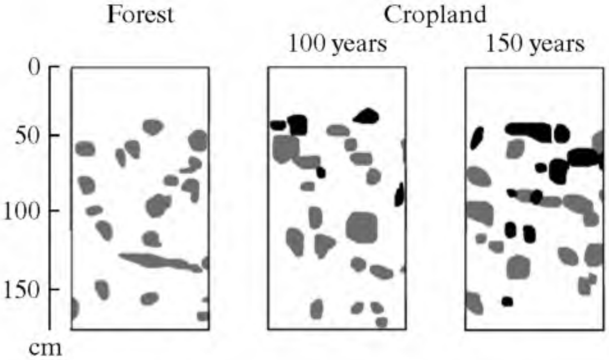

Fig. 1. Features of the burrowing activity of animals on the front walls of the soil pits. The recent mole tunnels are black, and the old mole tunnels are gray.

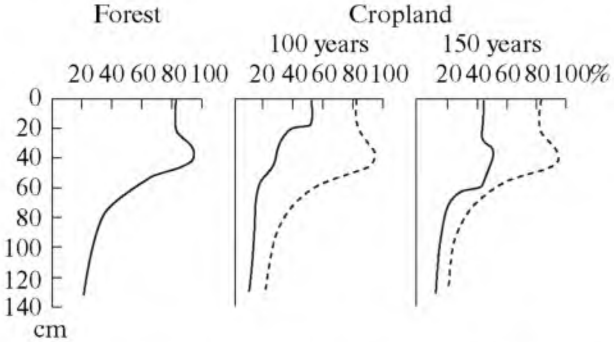

Fig. 2. Distribution of the sum of the aggregates of 1–10 mm in the soil profiles (for the plowed soils; the distribution of the aggregates in their virgin analogues is also shown by dotted lines).

The changes in the character of the zoogenic turbation of the soil profiles are illustrated in Fig. 1.

The results of the aggregate-size distribution analysis by the method of dry sifting attest to the worsening of the soil structure upon the plowing of the dark gray forest soil. The quality of the soil structure in the upper horizons (down to 47 cm) of the background forest soil is excellent, whereas the structure of the plowed soils is satisfactory or unsatisfactory. The worsening of the soil structure has taken place mainly at the expense of an increase in the content of very coarse (>10 mm) aggregates: 44% in the background forest soil and 64–74% in the plowed soils. The content of the silt-size (<0.25 mm) dry aggregates is about 1% in all the soils. Similar patterns of changes in the aggregate state of chernozems upon their plowing were described by Medvedev [8].

It should be noted that the changes in the soil structure upon the long-term soil cultivation are not unidirectional and proceed through certain stages. Thus, if we consider the most valuable aggregates (1–10 mm), we may see that their content decreased upon the cultivation of the dark gray forest soil. However, later (under the 150-year-old cropland), the structural state of the subsoil below the plow horizon somewhat improved (Fig. 2 and Table 3). These data are in agreement with the fact of the higher activity of burrowing animals improving the subsoil structure in the old-arable soil (Fig. 1). The conclusion about the improvement of the structural state of the subsoil in the old-arable gray forest soils is in agreement with our data on the agrogenic evolution of these soils obtained at other key sites in the southern part of the Central Russian Upland [19].

In the upper humus horizon, the coefficient of the water stability of the soil aggregates decreases from 0.85 in the background forest soil to 0.72–0.76 in the cultivated soils (Table 3 and Fig. 3b). However, in general, the water stability of the aggregates in the cultivated soils is very high or even excessively high. According to Medvedev [8], the coefficient of the water stability of the soil aggregates (the ratio of the amount of aggregates > 0.25 mm after the wet sifting to that after the dry sifting) is particularly informative for the purposes of monitoring of the soil's structural status.

An informative characteristic to compare particle-size distribution curves in the studied soil profiles is the coefficient of the textural differentiation calculated as the ratio of the contents (%) or reserves (t/ha) of clay in the illuvial part of the profile to those in the eluvial part of the profile. In our case, the illuvial part of the profiles includes the A2Bt (in the old-arable soil, the A1Bt), Bt1, and Bt2 horizons, and the eluvial part is represented by the plow layer (for the cultivated soils) and by the layer of 0–42 cm (from which the plow layer was formed) for the background virgin soil under forest.

Calculations based on the contents of the clay fraction (Table 3 and Fig. 3a) give us the following values of this coefficient: 1.26 for the background dark gray

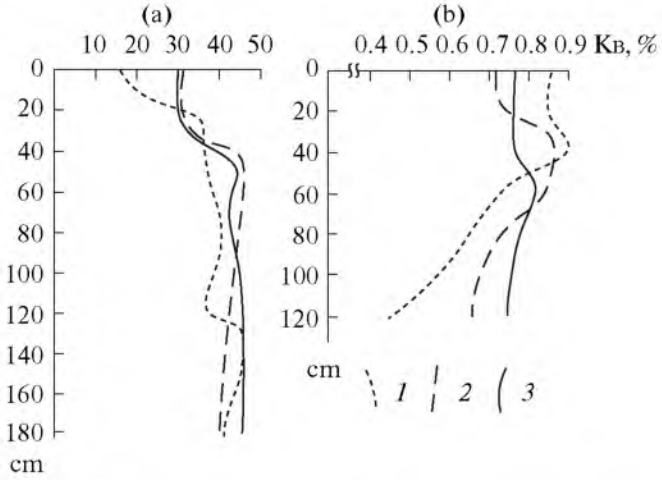

Fig. 3. Distribution of the (a) clay fraction (<0.001 mm) and (b) coefficient of the water stability of the soil aggregates in the (*1*) background (forest) soil, (*2*) soil of the 100-year-old cropland, and (*3*) soil of the 150-year-old cropland.

soil under forest vegetation, 1.38 for the soil of the 100-year-old cropland, and 1.41 for the soil of the 150-year-old cropland. Calculations based on the reserves of the clay fraction show the opposite trend: 1.65 for the background soil under the forest, 1.48 for the soil of the 100-year-old cropland, and 1.47 for the soil of the 150-year-old cropland. This variant of the calculations seems to be more accurate. Some decrease in the coefficient of the textural differentiation in the plowed soils can be explained by their homogenization under the impact of the burrowing activity of animals (Fig. 1). At the same time, the morphogenetic study of these soils attests to the presence of clear features of the downward migration of solid-phase soil components. The downward migration of suspensions is diagnosed by the presence of humus–clayey coatings on the walls of the deep fissures and by the concentration of skeletans in the zones of fissures immediately under the plow horizon. These features (including the deep fissures) are absent in the background forest soil. The translocation of clay and organomineral colloids from the upper part of the profile and their accumulation on the surface of soil aggregates in the illuvial horizons could contribute to some increase in the water stability of the soil structure in these horizons. The loss of these components from the plow layer favors the dispersion of the aggregates and the decrease in their water stability in this layer (Fig. 3b). Thus, the data on the particle-size distribution are in good agreement with data on the water stability of the soil aggregates.

According to the results of the physicochemical and chemical analyses (Tables 5 and 6), the long-term cultivation of the dark gray forest soil has led to some alkalization of the soil mass, especially in the lower horizons; the contents and reserves of pedogenic carbonates and available nutrients in the cultivated soils are higher than those in the virgin forest soil.

With respect to the reserves of available phosphorus and potassium, the soils cultivated for 100 and 150 years do not differ much from one another. However, they differ considerably from those in the background forest soil (Table 6). The positive balance of these elements in the cultivated soils may be explained by the application of mineral fertilizers.

The alkalization of the plowed dark gray soils is a result of the accumulation of carbonates in them. The latter process is enhanced by changes in the soil's climatic conditions after the substitution of crops for forest vegetation. This hypothesis is confirmed by the increased radiocarbon age of the carbonates in the oldest (150-year-old) arable soil (Table 4). The absence of permanent vegetation on the soil's surface leads to its stronger desiccation and to the ascending movement of solutions saturated with ancient carbonates from the parent material. This phenomenon was shown by us earlier for paleosol chronosequences buried under kurgans [17, 18].

The morphology of the carbonate concentrations was studied in the upper and lower calcareous BC_{Ca} horizons in all the soils. The micromorphological and *submicromorphological* (given in italics) descriptions and the data on the contents of the carbonate concentrations in the soil profiles are presented in Table 7 and in Figs. 4 and 5. The trends of the changes in the morphology of the pedogenic carbonates in the upper and lower parts of the calcareous layer under the agrogenic impacts are different.

In the upper horizons, the total content of pedogenic carbonates increases; they are clearly seen in the profile. The amount of collomorphic calcite also increases; collomorphic carbonates fill the pores and smoothen the relief of the mineral grains. The thickness of the collomorphic calcitic films also increases. The idiomorphic forms of pedogenic carbonates also become better shaped. It can be supposed that the calcite of the calcareous pedofeatures is subjected to in situ recrystallization via its transition into the colloidal solution and further precipitation without considerable translocation.

In the lower horizons, the amounts of both the collomorphic and idiomorphic forms of calcite increase. However, in general, the pedogenic carbonates become better crystallized and more segregated. The conditions of the crystallization are different, because both collomorphic calcite and crystals of different shapes are formed. It can be supposed that the crystallization of calcite in the lower soil horizons under the cropland proceeds from true solutions and has a gradual character. Under the forest, the precipitation of $CaCO_3$ from the colloidal solutions predominates.

Thus, in the upper calcareous horizons, the development of collomorphic calcite predominates in the plowed soils; the newly formed carbonates impregnate the soil mass. Their fast precipitation from the saturated solutions takes place. In the lower horizons, the pedogenic calcite is segregated into more pronounced pedofeatures; its crystallization from less saturated solutions proceeds for a longer time.

These data allow us to conclude that a significant transformation of the carbonate profile of dark gray forest soils takes place upon their agricultural development. This transformation has a staged pattern and is different in the upper and lower calcareous horizons.

One of the unexpected phenomena observed in our study is the stability of the humus reserves in the 1-m-deep soil layer of the virgin and plowed soils and an increase in the reserves of humus in the upper 50 cm of the plowed soils (Table 6). Note that the rate of application of organic fertilizers (farmyard manure) in the past two decades has been no higher than 4 t/ha per year; in the previous years, it was even lower. It is known that a zero budget of the humus in the cultivated soils of the central chernozemic zone can only be achieved upon the application of farmyard manure at a rate of no less than 10 t/ha [13]. According to Nikitin [10], a deficit-free humus budget in the arable

Table 5. Physicochemical and chemical properties of the studied soils

Horizon; depth, cm	pH		Humus	$CO_{2\,carb.}$	Exchangeable bases, meq/100 g			N_{tot}, %	Nitrite N	NO_3^-	S	Available forms, mg/100 g	
	H_2O	KCl	%		Ca^{2+}	Mg^{2+}	total		mg/kg			P_2O_5	K_2O
Broadleaved forest													
A1 (3–13)	6.56	5.64	3.56	None	18.5	3.75	29.6	0.28	67.6	3.90	5.5	8.0	20.1
A1A2 (13–21)	6.52	4.86	3.08	None	16.5	2.75	24.74	0.23	2.51	1.10	0.0	7.1	10.7
A1A2Bth (21–47)	6.43	4.77	2.34	None	21.3	3.25	26.64	0.17	1.35	1.20	0.0	13.3	11.4
A2Bt (47–65)	6.62	4.68	1.39	None	23.0	3.50	26.84	0.19	0.98	0.96	0.0	16.4	12.4
Bt1 (65–80)	6.95	4.84	0.95	None	23.8	3.50	27.47	0.19	0.96	0.85	2.7	17.1	16.1
Bt2 (80–103)	7.26	5.04	0.82	None	24.0	3.75	27.83	0.09	1.55	1.32	3.5	13.2	15.0
BtC_{Ca} (103– 120)	7.36	5.70	0.75	0.40	25.0	3.75	28.98	0.11	1.10	1.06	1.0	–	–
BC_{Ca} (120–155)	8.25	7.05	0.74	4.25	27.5	3.50	k	0.15	1.12	1.02	2.7	–	–
C_{Ca} (155–170)	8.62	7.23	0.68	4.69	27.5	2.75	k	0.13	1.55	1.48	4.9	–	–
C_{Ca} (170–190)	8.28	7.24	0.61	4.82	28.5	2.75	k	0.12	1.38	1.32	8.2	–	–
C_{Ca} (190–210)	8.30	7.23	0.61	4.47	28.5	3.00	k	0.11	0.98	0.96	15.0	–	–
C_{Ca} (210–230)	8.30	7.25	0.64	4.93	28.5	2.88	k	0.10	1.10	0.91	16.0	–	–
Cropland, 100 yrs													
Ap' (0–20)	6.94	5.87	3.30	None	18.8	2.75	26.05	0.22	11.5	3.30	2.2	18.5	24.5
Ap" (20–33)	7.10	5.91	2.95	None	18.5	3.13	26.63	0.21	17.0	2.75	0.0	12.1	12.7
A1A2Bth (33–43)	6.86	5.39	1.87	None	22.0	3.25	27.80	0.16	2.63	1.48	0.0	9.7	11.0
A2Bt (43–65)	6.95	5.09	1.06	None	21.8	3.75	26.27	0.22	1.95	1.18	0.0	9.5	10.2
Bt1g (65–90)	7.12	5.24	0.64	None	22.5	3.25	27.02	0.13	1.55	1.29	0.3	11.9	9.7
Bt2g (90–110)	8.16	6.85	0.56	0.84	27.5	3.00	k	0.10	1.91	1.41	3.0	27.2	17.2
BtC_{Ca} (110–130)	8.38	7.10	0.51	2.88	25.0	2.75	k	0.10	1.91	1.38	3.0	–	–
BC_{Ca} (130–150)	8.32	7.33	0.51	6.39	26.3	3.25	k	0.10	1.23	1.12	3.1	–	–
C_{Ca} (150–170)	8.44	7.31	0.50	5.49	26.5	3.25	k	0.09	1.23	1.12	4.2	–	–
C_{Ca} (170–190)	8.46	7.26	0.47	4.69	26.0	3.75	k	0.13	1.78	1.51	4.6	–	–
C_{Ca} (190–210)	8.43	7.27	0.34	4.58	26.8	4.0	k	0.08	2.04	1.45	10.1	–	–
Cropland, 150 yrs													
Ap (0–30)	6.69	5.60	3.32	None	16.8	2.75	25.56	0.22	40.7	20.4	2.0	23.4	26.0
A1 (30–48)	6.76	5.23	2.09	None	18.8	3.25	24.49	0.21	12.0	7.60	0.0	9.0	17.1
A1Bt (48–60)	6.65	4.81	1.13	None	22.0	3.38	26.91	0.12	5.9	5.60	0.0	7.0	11.7
Bt1 (60–80)	7.20	4.52	0.78	None	22.5	4.0	27.79	0.13	5.5	4.90	0.0	6.0	11.0
Bt2 (80–100)	6.99	5.10	0.65	0.30	25.0	3.75	29.38	0.10	5.6	4.60	0.6	12.6	9.2
$BtCg_{Ca}$ (100–130)	8.42	7.19	0.53	4.81	26.8	2.75	k	0.07	3.7	3.50	4.4	–	–
$BtCg_{Ca}$ (130–160)	8.42	7.21	0.50	5.40	27.3	2.75	k	0.09	3.2	2.24	5.3	–	–
BCg_{Ca} (160–180)	8.38	7.13	0.45	3.65	28.5	3.25	k	0.09	3.7	3.59	9.4	–	–
Cg_{Ca} (180–200)	8.43	7.19	0.45	3.98	28.8	3.25	k	0.09	3.9	3.50	9.6	–	–
Cg_{Ca} (200–220)	8.53	7.17	0.40	3.05	29.0	4.0	k	0.08	4.0	3.50	9.6	–	–

Note: The letter k denotes the presence of carbonates (effervescence); the dashes denote the absence of determinations.

Table 6. The reserves of humus, carbonates, and some nutrients in the soil profiles

Indices	Layer, cm	Soil		
		forest	cropland, 100 yrs	cropland, 150 yrs
Humus, t/ha	0–25	84	109	114
	0–50	157	181	191
	0–100	234	235	259
P_2O_5, kg/ha	0–25	2.0	6.1	7.7
	0–50	6.6	9.8	10.6
	0–100	18.3	21.0	17.2
K_2O, kg/ha	0–25	4.2	7.7	8.7
	0–50	8.1	11.6	14.2
	0–100	18.7	19.9	21.2
$CaCO_3$, t/ha	100–200	2180	2710	2800

Table 7. Distribution patterns of the carbonates in the soil profiles

	Upper calcareous horizon	Lower calcareous horizon
Forest	No migration of calcite through the pores; the pores are virtually empty. The plasma is saturated with dispersed carbonates; there are also small carbonate nodules and loci of carbonate concentrations in the soil mass (Fig. 4a). *The carbonate nodules are loose and consist of amorphous and fine-crystalline calcite of irregular shape. The collomorphic carbonate films are very thin and evenly cover the silicate material. The pores are empty. The calcite grains in the soil mass have distinct etching figures (Fig. 4c).*	Carbonate concentrations are present in the pores; the content of calcite in the plasmic material is lower than that in the upper calcareous horizon (Fig. 4b). *The carbonate concentrations in the pores are more pronounced and consist of large amorphous masses; the collomorphic films on the silicate grains are much thicker than those in the upper horizon, so the initial relief of the grains is not seen (Fig. 4d).*
Cropland, 100 yrs	Acicular calcite appears in the pores and partly penetrates into the surrounding soil mass (this form is absent in the forest soil). Abundant carbonate concentrations are seen in the pores. The plasmic material is reorganized due to the appearance of considerable amounts of calcite (Fig. 4e). *The carbonate nodules consist of very-fine-crystalline calcite; imperfect acicular calcite crystals are also present in them. The collomorphic nature of the calcite is clearly pronounced. The pores are partly filled with calcite (Fig. 4g).*	The soil plasma is saturated with carbonates; there are also carbonate concentrations in the pores and in the intraped mass; microzones with skelsepic plasmic fabric are seen (Fig. 4f). *Diverse forms of calcite crystals: coarse and fine, acicular, rod-shaped, and flocculated. Calcitic films of varying thickness cover the S-matrix. The pores are almost filled with calcitic material with a predominance of amorphous forms (Fig. 4h).*
Cropland, 150 yrs	Very few pores are filled with growths of acicular calcite crystals. The lattisepic fabric of the clayey–calcareous mass predominates; there are also microzones with skelsepic plasmic fabric. Most of the skeletal mineral grains are covered by the carbonate plasma; the crystalline structure of this carbonate material is not seen under a microscope (Fig. 4i). *Thick coatings of collomorphic calcite on mineral grains and on pore walls; separate crystals are seen on the surface of these coatings (Fig. 4k).*	Disintegrated large carbonate concentrations in the plasma. Features attesting to translocation of separate calcite grains and fragments of carbonate concentrations can be seen in the pores. In some zones, such concentrations penetrate into the intraped plasmic material, though the separation of the carbonate concentrations from the plasma is very distinct. Micrograined calcite predominates (Fig. 4j). *The carbonate concentrations are composed of clearly crystalline calcite; their morphology is close to the morphology of the beloglazka (white eyes) in the steppe chernozems. The calcite crystals have distinct growth planes. The pores are almost filled with collomorphic calcite (Fig. 4l).*

gray forest soils is achieved upon the annual application of 30–35 t/ha of manure.

Let us analyze the data on the radiocarbon ages and reserves of humus. The humus from the upper soil layer (0–42 cm in the background forest soil, or 0–35 cm in the plowed soils with a higher bulk density of the upper horizons) has a clear tendency for a decrease in its age with an increase in the duration of the agrogenic impact: 1920 ± 70 yrs in the background forest soil, 1430 ± 50 yrs in the soil of the 100-year-old cropland, and 1410 ± 60 yrs in the soil of the 150-year-old cropland (Tables 2 and 5). At the same time, the reserves of

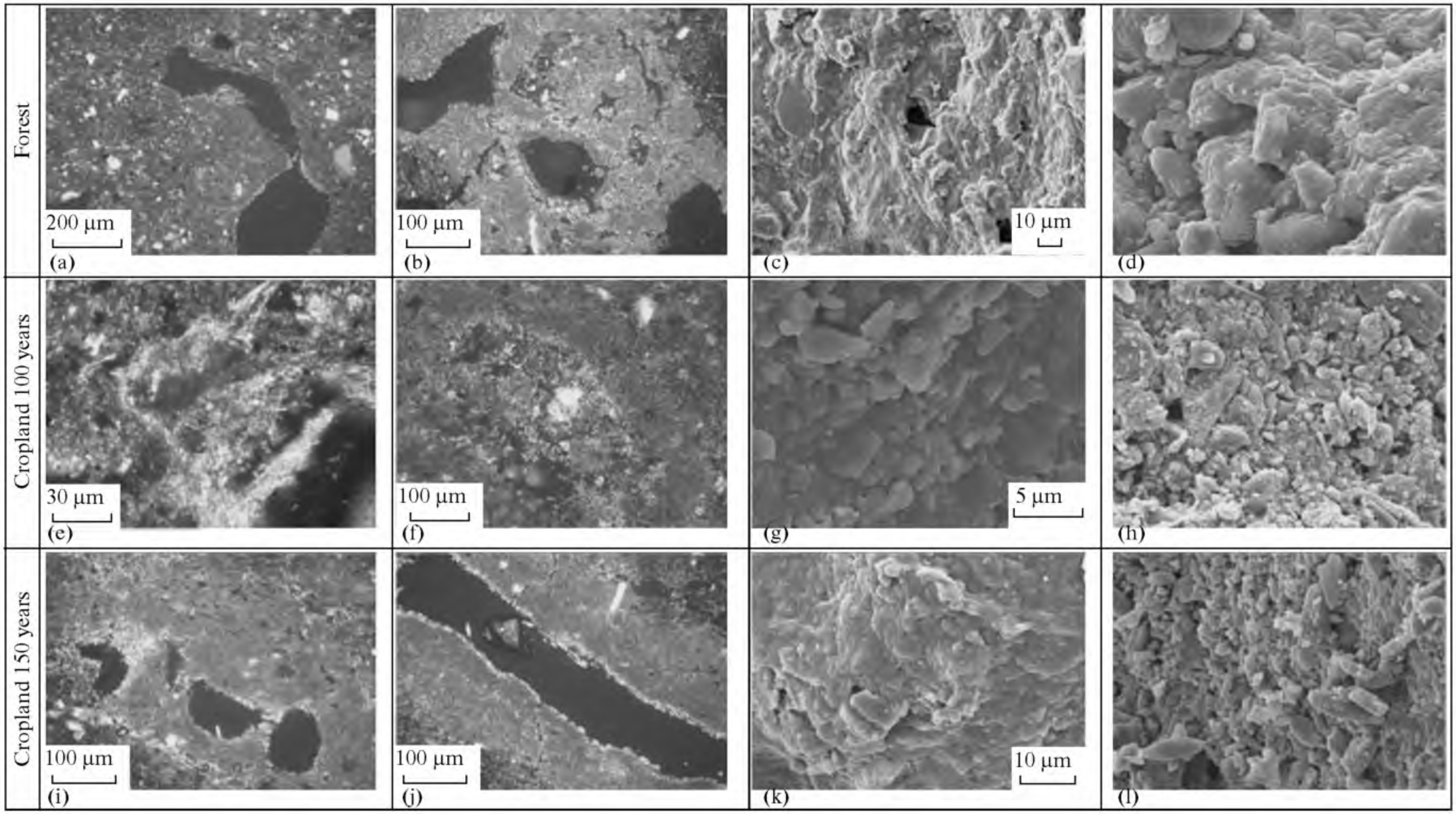

Fig. 4. Microphotography of the pedogenic calcite in the studied soil profiles.

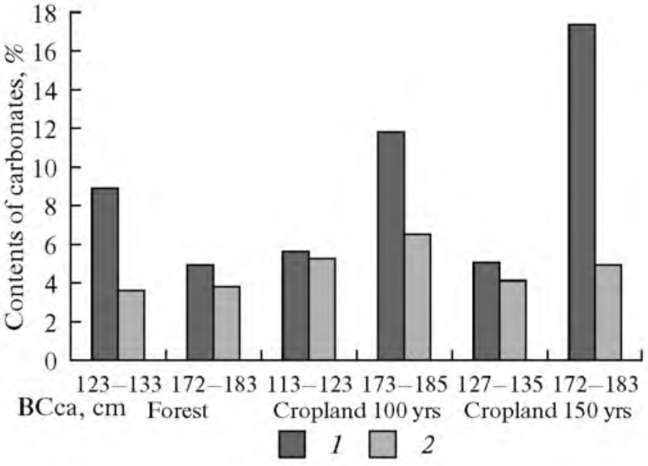

Fig. 5. Distribution of (*1*) segregated and (*2*) dispersed carbonates in the studied soils. Numbers under each of the paired samples indicate the depths of sampling (cm) from the upper and lower calcareous horizons.

humus in the considered layers (Table 6) display the opposite tendency; they increase with an increase in the duration of the agrogenic impact: 140 t/ha (forest soil), 150 t/ha (cropland, 100 yrs), and 154 t/ha (cropland, 150 yrs). It can be supposed that humic substances in the plow horizons are being rejuvenated owing to the input of freshly humified organic matter. This result should be carefully verified in the future. However, it is not the only example of a rise in the content and reserves of humus in the old-arable gray forest soils of the forest-steppe zone (provided that soil erosion is absent). Similar data were obtained in the study of the agrogenic evolution of gray forest soils on other key plots in the central forest-steppe area [14, 19].

A striking example of the opposite direction of the temporal changes in the pools of humus in the plow horizon of steppe chernozems and forest-steppe gray forest soils is presented by the results obtained at the points studied by Dokuchaev during their repeated study over a century (Table 8).

CONCLUSIONS

As follows from our research, the transformation of virgin automorphic dark gray forest soils under the impact of continuous cultivation for 150 years is clearly manifested in a number of the morphological, physical, and other soil properties and proceeds with a high rate.

The old-arable analogue of the virgin dark gray forest soil is characterized by a deeper thickness of the humus layer, a higher degree of pedoturbation by burrowing animals, a more alkaline soil reaction, and a higher content of pedogenic carbonates. According to the morphogenetic, physicochemical, and chemical properties of this soil, it should be classified as a medium-deep slightly podzolized chernozem.

In the evolutionary sequence from the dark gray forest soil to the podzolized chernozem, certain stages of changes in the qualitative composition of the soil carbonates can be traced. In turn, they reflect the changes in the hydrothermic conditions of the pedogenesis after the substitution of crops for the natural forest vegetation.

The processes of chernozemic pedogenesis in the cultivated dark gray forest soils are combined with the processes of the eluvial–illuvial redistribution of substances. The latter are manifested by the concentration of whitish skeletans in the zones around deep vertical fissure in the upper part of the soil and by the formation of clayey–humus coatings on the walls of the fissures in the lower part of the soil. With an increase in the duration of the continuous soil cultivation, the eluvial–illuvial processes in the plowed soil become masked by the zoogenic turbation of the soil by bur-

Table 8. Comparative data on the humus content in the plow horizon of soils in Kursk oblast, % (from [9])

Location of the soil pits	Soil	1883	1983
L'gov	gray forest	3.01	3.92
Korenevo	"	2.07	2.30
Tuskar' River	"	3.30	4.02
Ponyri	chernozem	6.11	5.71
Mar'ino (Rzhava)	"	6.03	5.72
Ploskoe	"	7.32	6.52
Okhochevka	"	7.30	6.18

rowing animals, the more pronounced accumulation of humus, and the structuring of the lower soil horizons with an increase in the water stability of the soil aggregates in the middle and lower parts of the soil's profile. The relationships between these processes and their seasonal dynamics require further studies.

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