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Dynamics of Soil Acidity, Structural–Aggregate State, and Carbon Stocks in Agro-Dark-Humus Podbels in the Postagrogenic Development

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Abstract—Changes in the structural–aggregate state, acidity, and carbon stocks of dark-humus podbels (Luvic Albic Mollic Planosols (Epiloamic, Endoclayic, Aric)) during their postagrogenic development under unmanaged fallow were studied at the experimental station of the A.K. Chaika Federal Scientific Center of Agricultural Biotechnology of the Far East. Restoration of the aggregate state of the soil after its removal from agricultural use took place: the content of agronomically valuable aggregates increased and their weighted average diameter decreased in the former arable layer. In the course of vegetation restoration, soils were acidified. The most pronounced drop in pH took place in the 20-yr-old fallow soil with the appearance of woody plants. The content and stocks of carbon in the fallow soils tended to increase during the entire studied postagrogenic period. Carbon stocks in a layer of 0–25 cm reached their maximum by the 85th yr of the postagrogenic succession. However, the difference between carbon stocks in a layer of 0–50 cm in the 20- and 85-yr-old fallow soils was statistically insignificant. Bulk density of the plow layer in the cultivated soil reached 0.88 g/cm^3. In the fallow soils, bulk density of the upper horizon varied within 0.67–0.79 g/cm^3.

Keywords: abandoned land, fallow land, soil structure, dark-humus agropodbels, Mollic Planosols

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INTRODUCTION

The conversion of a part of arable land into unmanaged fallow is a natural process in the development of agriculture. In countries with developed agriculture, there are lands, the use of which becomes inefficient with constantly changing pricing and other economic reasons. On a global scale, approximately 1.5×10^6 km^2 of arable land was abandoned from 1700 to 1990 [41]. The greatest reduction in cultivation areas was noted in economically developed countries with mountainous areas, including Eastern Europe [24, 27], Southeast Asia [35], and the former Soviet Union [13, 19, 32, 34].

The economic crisis in the early 1990s in Russia contributed to a sharp reduction in cropland area. According to the agricultural census of 2016 (the latest at the moment), the total area of unused land in Russia is 97.2 million hectares, which corresponds to 44% of the total area of arable fund [7].

When abandoned agricultural land is overgrown, especially after its long-term use, the main physical, chemical, and biological properties of the upper soil horizons change considerably [18, 19, 27, 28]. Changes in the soil organic matter content during the postagrogenic soil development are of great interest for Russian and foreign researchers [1, 16, 17, 19, 28, 30, 32–34, 36, 39, 40, 44, 46]. According to many researchers, with an increase in the period of absence of agricultural load, the carbon content in the soil increases. Certain patterns have been established between the age of fallow land and the rate of carbon accumulation in the soil [19, 32, 34, 40]. The accumulation rate varies widely, averaging 10–30 g C/m^2 per yr [36, 39, 40]. The rate of carbon accumulation in the fallow soils of Russia 20 yr after the removal of the anthropogenic load reaches 105 g C/m^2 per yr [33].

Despite a large number of studies devoted to this problem, there is no unequivocal opinion on the direction and nature of the dynamics of the carbon content and stocks in postagrogenic soils. Some studies have shown that the carbon content in fallow soils can vary slightly [30] or even decrease [13, 46]. Many factors affect the rate of change in carbon stocks, such as bioclimatic conditions, soil type and properties, and past agricultural use patterns.

The stability of soil aggregates depends on the organic matter content. The number, size, and stabil-

Table 1. Characteristics of study objects

Land use, age	Soil	Dominant synusia	Coordinates	
			latitude N	longitude E
Arable land, 0 yr	Dark-humus gleyed agropodbel	Soybean	43°51′33.4″	131°56′41.4″
Fallow land, 2 yr	Regraded dark-humus agropodbel	Grass	43°51′23.4″	131°56′33.3″
Fallow land, 5 yr	Regraded dark-humus agropodbel	Grass	43°51′26.3″	131°56′29.2″
Fallow land, 20 yr	Gleyic regraded dark-humus agropodbel	Forb–grass	43°51′36.5″	131°56′15.5″
Fallow land, 85 yr	Postagrogenic dark-humus podbel	Forb–grass–wormwood	43°51′32.6″	131°56′38.2″

ity of soil aggregates largely determine the nature of changes in soil properties [1, 17, 38, 47]. Soils dominated by macroaggregates contain more organic matter and nutrients, are less susceptible to erosion, and provide optimal conditions for plant growth [43–45].

The long-term agricultural use of soils is accompanied by the disturbance of the aggregate state of the topsoil [25, 42]. Macroaggregates have poor stability and can be destroyed under systematic agricultural loads, both due to the mechanical impact of heavy equipment, and due to a decrease in the supply of fresh organic matter [1, 17]. With the removal of agricultural load, the aggregate composition of soils undergoes serious changes, which is due to the restoration of the natural biocenosis on fallow lands and the influence of factors inherited from arable lands.

Over the past few yr, the Russian agricultural industry has been demonstrating high growth rates. Restoration of the properties of fallow soils and their rational use at different stages of succession are of great interest because of the economic cost of returning unmanaged fallow to agriculture varies greatly depending on the age and quality of the fallow.

This study is aimed at determining postagrogenic changes in the aggregate state and acidity of dark-humus agropodbels, as well as in the carbon stocks of these soils during their natural restoration under the unmanaged fallow.

OBJECTS AND METHODS

The study was carried out in the area of Timiryazevskii settlement (Ussuriisk district, Primorskii region) in July–August 2021. The studied soils were classified as dark-humus agropodbels, or Luvic Albic Mollic Planosols (Epiloamic, Endoclayic, Aric) according to the WRB system [48]. We studied soils of 2-, 5-, 20-, and 85-yr-old fallow plots at the experimental field of the A.K. Chaika Federal Scientific Center of Agricultural Biotechnology of the Far East, as well as plowed soils of the field experiment (Table 1). Fallow plots had been used in rotation systems in the past. The 85-yr-old fallow was subjected to mowing once a yr at the end of the growing season (September–October).

Dark-humus podbels (PU–ELnn–BTnn–BT–C) are developed from lacustrine-alluvial deposits and are characterized by the high humus content and clayey or heavy clayey texture (the content of clay particles in the upper horizon reaches 80–85%). The high bulk density of the upper horizons contributes to the low water permeability. These soils are widespread within the Zapadnoprimorskaya and Sredneamurskaya plains [2, 4, 6]. Dark-humus podbels form the basis of the arable fund of the Primorskii region (34.5% of the valuable arable land in the region) [9].

Dark-humus podbels are formed under forb–grassy vegetation. Plant communities of the studied young fallow plots (2 and 5 yr) are characterized by low species diversity. The grass layer is well developed; its average height does not exceed 1 m, and dominant species are represented by *Phleum pratense*, *Calamagrostis langsdorffii*, and *Elytrigia repens*. In the 20-yr-old fallows, the grass–form community is established, and young growths of *Salix* sp. appear. *Phleum pratense*, *Calamagrostis langsdorffii, Galium verum*, *Vicia amurensis*, and *Artemisia rubripes* predominate among herbage with the average height of 50–70 cm. *Elytrigia repens*, *Calamagrostis langsdorffii*, *Phleum pratense*, and *Artemisia rubripes* are the dominant species on the periodically mown 85-yr-old fallow plot.

A stationary experiment with the systematic long-term application of various types of fertilizers has been carried out on the experimental fields since 1941. We took mixed soil samples from soil horizons along the entire soil profile in the main pit and three additional test pits on the plot with the use of organic fertilizers: manure at the rate of 240 t/ha per yr (from 1941 to 2003) and green manure (legumes and grasses) plowed into the soil (from 2004 to the present). The accounting area of the experimental plot was 150 m^2. Soil sampling from fallow plots was carried out from test pits (three pits on each field) from the depths of 0–25 and 25–50 cm. Soil samples were air-dried. The upper part (0–4 cm) of the PU horizon at the 85-yr-old fallow plot was characterized by the dense sod. This layer was separated and not used in the analytical work to eliminate the distortion of the results.

The aggregate composition of the soil mass was determined by dry sieving using a Retsch AS 200 basic vibratory sieve shaker (Germany). A sample of air-dry soil (300 g) was passed through a set of sieves with mesh sizes of 10, 5, 2, 1, 0.5, and 0.25 mm. Shaking

Table 2. Dynamics of pH and the carbon content in the arable and fallow dark-humus podbels of different ages

Age of fallow	Layer, cm	pH_{KCl}	C_{tot}, %
0 yr (arable land)	0–27	5.08 ± 0.10	1.37 ± 0.04
	27–42	5.05 ± 0.08	1.46 ± 0.05
2 yr	0–25	6.05 ± 0.15	1.74 ± 0.07
	25–50	5.19 ± 0.11	1.52 ± 0.05
5 yr	0–25	5.23 ± 0.10	1.89 ± 0.05
	25–50	4.57 ± 0.9	1.13 ± 0.04
20 yr	0–25	4.51 ± 0.7	2.21 ± 0.09
	25–50	4.46 ± 0.9	1.64 ± 0.06
85 yr	4–11	5.08 ± 0.8	4.31 ± 0.12
	11–35	5.1 ± 0.07	1.68 ± 0.08
	35–55	4.72 ± 0.07	0.63 ± 0.02

time was 2 min, vibration amplitude was 2.5 mm [20]. In the analysis, the structural coefficient (*K*s), the proportion of agronomically valuable aggregates (AVA) of 0.25–10 mm in size, and the weighted average diameter of aggregates were calculated [23, 29].

The total carbon content (C_{tot}) was determined by chromatography using a Flash 2000 elemental analyzer (Thermo, Great Britain); soil acidity (pH of salt extract) was determined on a Mettler Toledo S220-Kit pH meter (Switzerland).

Statistical treatment of the data was carried out according to generally accepted methods using Statistica v.13 software. The Mann–Whitney test (U test) was used to compare the data of independent samples.

The samples were studied in a specialized laboratory, as well as using the technical facilities of the Collective Use Center for Biotechnology and Genetic Engineering (Federal Scientific Center of Biodiversity, Far East Branch of the Russian Academy of Sciences).

RESULTS AND DISCUSSION

In the studied fallow plots, the least acid reaction of the medium in the upper part of the profile was noted in the soil of a 2-yr-old fallow (Table 2). Probably, this was due to the long-term application of organic fertilizers (before the conversion of the plot into the unmanaged fallow) and an increased supply of ash elements with abruptly changing vegetation, which contributed to the neutralization of organic acids [18]. In the 5-yr-old fallows, the pH value was 5.2; 20 yr after the end of agricultural use, with the appearance of tree species, it decreased to 4.5. During postagrogenic succession, soil acidification is a natural process as noted by many authors [12, 13, 16, 18, 28, 31]. An increase in acidity is largely associated with a change in the composition of plant litter and the formation of a litter horizon, especially at the stage of reforestation.

The use of high rates of organic fertilizers slows down the increase in the acidity of arable soils [18]. In the studied plot of the experiment with the application of organic fertilizers, the pH of the upper horizon was 5.08. In 2009–2013, the pH of the plow horizon at these fertilized plots was 5.3 [2].

The pH_{KCl} of the soil of the mown fallow 85 yr after the end of plowing was 5.08. This was probably due to a smaller amount of acid products of decomposition of organic residues as compared with the unmown plots, where their input was higher [16, 22].

Data on the aggregate state of the studied soils are shown in Fig. 1. In the upper layer of both fallowed and plowed soils, the soil structure is excellent. The highest value of the structural coefficient *K*s (8.11) is in the upper horizon of the 5-yr-old fallow plot. In the plow horizon of the arable soil, this coefficient is 4.38. This is the only soil, in which the *K*s in the subsurface layer (25–42 cm) is higher than that in the surface layer (0–25 cm). The plow layer and the underlying horizon of the arable soil do not differ much with respect to the content of the coarse (>10 mm) aggregate fraction, which may be associated with deep moldboard plowing and soil compaction under the load of agricultural machinery [10, 37]. The weighted average diameters of aggregates also differ insignificantly (4.0–4.2 mm). The content of AVA in the subsurface horizon increases in comparison with the that in the plow horizon simultaneously with a decrease in the content of silt-size aggregates. It should be noted that *K*s and the AVA content in the plow horizon of the arable soil are lower than those in the fallow soils.

In the upper horizon of the 2-yr-old fallow, aggregate fractions > 5 mm in diameter predominate (Fig. 2). Because of this, the weighted average diameter of aggregates in the surface horizon is greater than that in the other fallow plots. This may be related to the deep plowing of this soil before its conversion into the unmanaged fallow. In the subsurface horizon, the content of aggregates >5 mm in diameter decreases

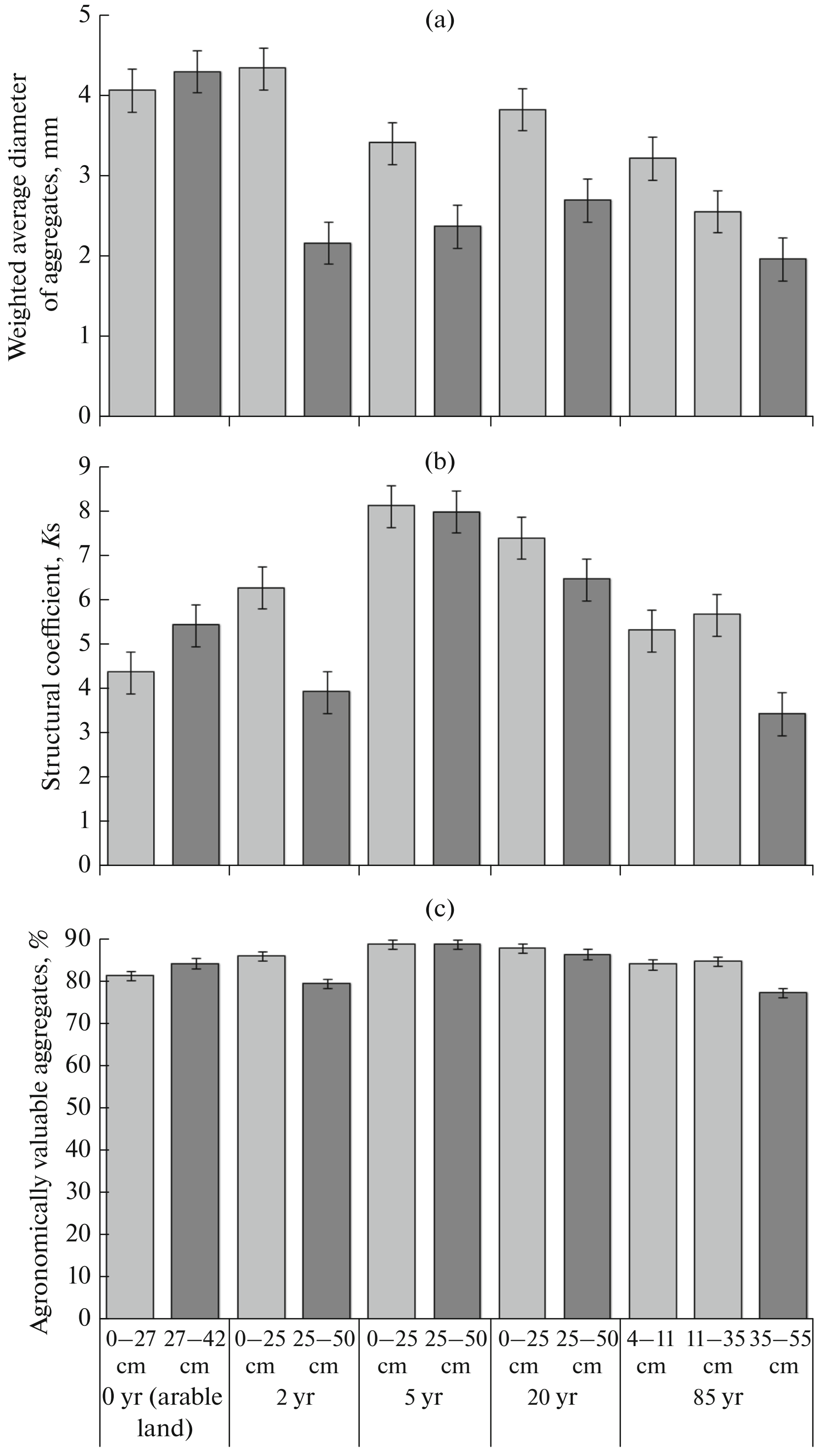

Fig. 1. Indicators of the aggregate state of arable and fallow dark-humus agropodbels of different ages: (a) weighted average diameter of aggregates, (b) structural coefficient, and (c) agronomically valuable aggregates.

with a simultaneous increase in the content of the fine sand and silt-size (<0.25 mm) aggregate fractions. This is explained by the fact that the main root system of herbaceous plants in the young fallow soil is concentrated in the upper layer. This horizon becomes looser and more permeable; fine fractions from the surface layer are washed out into the subsurface layer [3, 5]. The structural coefficient in the former plow horizon is two times higher than that in the underlying layer.

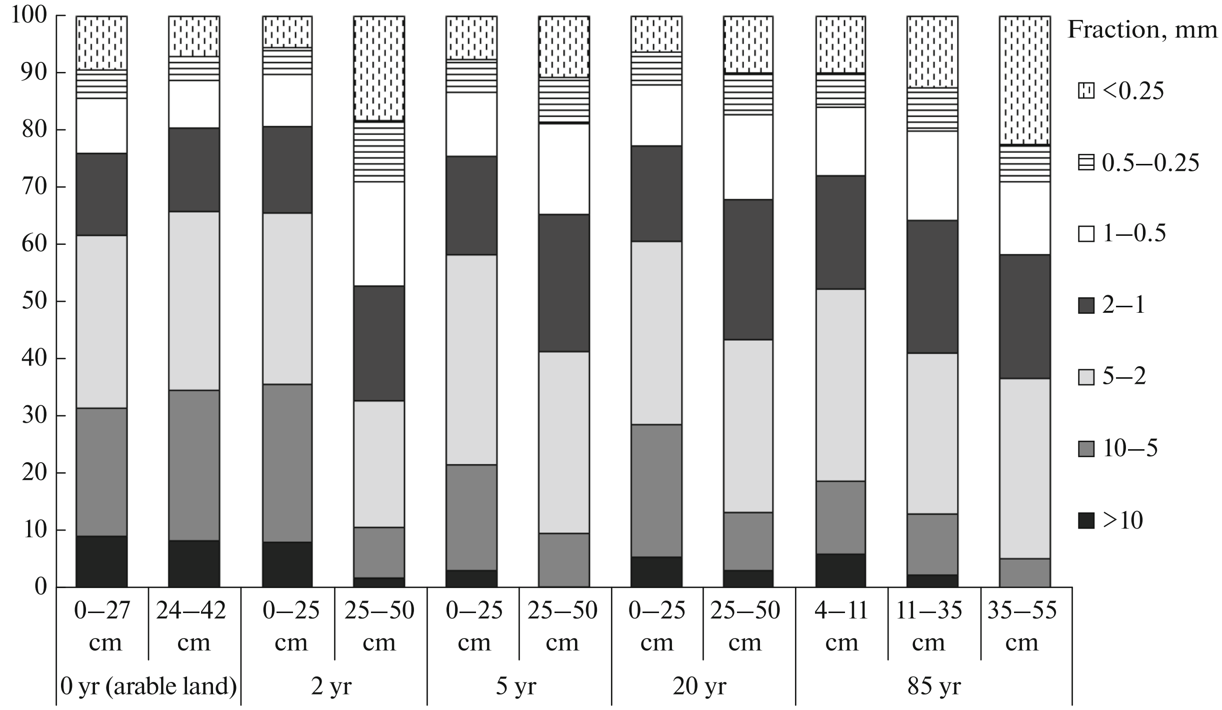

Fig. 2. Distribution of aggregate fractions in arable and fallow dark-humus agropodbels of different ages.

Overgrowing of the arable land for five yr contributed to a significant improvement of the structure of the upper soil horizons. The structural coefficient in the layer of 0–25 cm layer increased to 8.1, and the amount of AVA increased to 89%. In the subsurface horizon, these indicators are somewhat lower. The improvement of the structure was due to a decrease in the content of the coarse (>10 mm) aggregate fraction and an increase in the content of the aggregate fraction of 2–5 mm, especially in the subsurface horizon.

After 20 yr of fallowing, the former plow horizon has an excellent structural state; the structural coefficient is 7.4, which is 60% higher than in the arable soil. In contrast to younger fallow plots, the aggregate composition is characterized by a slight increase in the contents of the coarse (>10 mm) fraction and aggregates of 5–10 mm in diameter. Visually, these are large dense subangular blocky aggregates held together by the roots of herbs. At the same time, some compaction of the horizons takes place because of a more compact packing of structural units aligned in the size. Probably, anthropogenically transformed horizons undergo changes leading to differentiation and formation of the original humus horizon [19]. Previously, it was noted [3, 26] that in the fallow soils of the study area, the restoration of the soil structure destroyed as a result of mechanical tillage begins after 15–20 yr.

The upper layer of the 85-yr-old fallow has a lower *K*s compared to younger postagrogenic areas, which is probably due to pedogenic stratification of the plow horizon and the formation of the dense sod layer at the surface (0–4 cm). The highest *K*s values are in the layer of 11–35 cm with the maximum content of AVA. This is associated with a decrease in the content of the coarse aggregate fraction. Aggregates >10 mm in diameter are absent in the layer of 35–55 cm, whereas the content of aggregates <0.25 mm in diameter increases.

In general, the studied fallow soils are characterized by an improved structural state compared to the modern arable soil. Our data are consistent with the conclusions of other researchers attesting to an improvement of the aggregate state of soils after the cessation of anthropogenic loads [3, 26, 32, 43, 44].

The main difference between fallow soils and arable soils is the transformation of the humus-accumulative part of the profile. Anthropogenically transformed horizons undergo changes leading to differentiation and formation of the original humus horizon [8, 16, 18, 19, 27, 28]. In the studied soils, a clear differentiation of the former arable horizon is noted in the 85-yr-old fallow, the upper part of which has the dense sod layer with a huge number of the roots of herbs.

Our study indicates that dark-humus podbels are characterized by a low carbon content, which is typical for the soils of the region [14, 21]. The C_{tot} content in the layer of 4–11 cm of the soil of the 85-yr-old fallow is 4.31%. In younger fallows, the C_{tot} content in the upper horizon is significantly lower. It should be noted that the 85-yr-old fallow is periodically mown, so that the main source of organic matter is removed from the field. According to some data [11], periodic exclusion

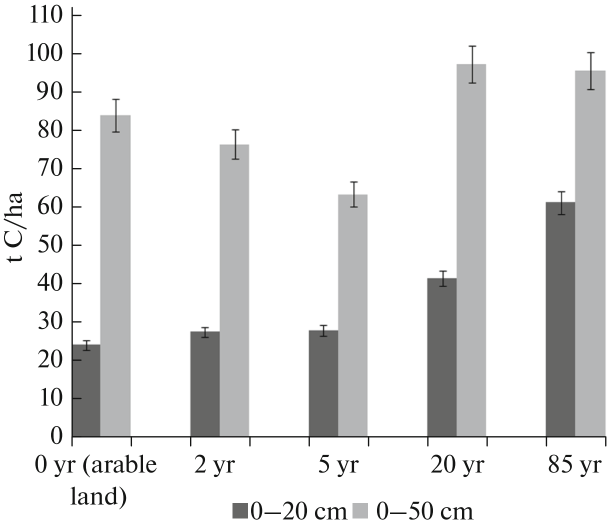

Fig. 3. Carbon stocks in arable and fallow dark-humus agropodbels of different ages.

of herbage during the long-term postagrogenic succession contributes to an increase in the accumulation of C_{tot} in comparison with that in the unmown soils. In general, in the studied chronological series, the C_{tot} content tends to increase with an increase in the duration of the postagrogenic period, which is consistent with the results of other researchers [15, 18, 32, 34, 36, 40].

The arable soil is characterized by the lowest C_{tot} content in the plow layer. At the same time, the C_{tot} accumulation is seen in the subsoil, which may be associated with the long-term application of manure [18, 32] simultaneously with mixing of the soil mass of the horizons during plowing [14]. In the soils of all the studied fallows, the C_{tot} content decreases with depth.

With the development of postagrogenic succession, carbon migration increases and its redistribution in the soil profile takes place. Carbon stocks in the upper horizon (0–25 cm) increase after the end of plowing reaching a maximum in the 85-yr-old fallow soil (Fig. 3). After the conversion of arable land into the long-term unmanaged fallow, carbon stock in the layer of 0–50 cm somewhat decreased, which was probably associated with a sharp decrease in the input of organic matter in the form of manure. The positive dynamics of carbon stocks began 5 yr after the beginning of the postagrogenic succession; carbon stocks increased significantly in 20 yr. The difference in carbon stocks of the layer of 0–50 cm in the soils of the 20- and 85-yr-old fallow plots was statistically insignificant.

CONCLUSIONS

Traditional methods of agriculture lead to a deterioration of the aggregate state of the soil. The content of the coarse aggregate fraction (>10 mm) in the arable soil is higher than that in the fallow soil. The structural coefficient and the number of agronomically valuable aggregates in the subsoil is higher than that in the plow layer because of the regular mechanical impact on the soil. The removal of dark-humus soils from agricultural use contributes to the improvement of the aggregate state of the soil. The structural coefficient in the soil of the 20-yr-old fallow reaches 7.4 and exceeds that in the plow horizon by 60%.

With the postagrogenic restoration of vegetation, some acidification of the soil takes place, which is associated with a change in the composition of plant litter and the formation of the sod layer. It is most pronounced in the soil of the 20-yr-old fallow with the appearance of tree species. In the upper horizon of the 85-yr-old fallow subjected to periodical mowing, as well in the plow horizon of the modern arable soil, the pH_{KCl} value is 5.08.

The carbon content steadily increases during the entire period of the postagrogenic succession. Carbon accumulation takes place due to a considerable rise in the phytomass, the absence of alienation of plant material, and the formation of the litter horizon. However, in the first yr after the end of soil cultivation, carbon stocks in the layer of 0–50 cm somewhat decreased because of the absence of the regular application of manure. In the 20-yr-old fallow soil, carbon stocks in the upper 50 cm reach 97.4 t C/ha, which is 65% higher than in the 2-yr-old fallow soil.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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