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SOIL CHEMISTRY

Assessment and Prediction of Changes in the Reserves of Organic Carbon in Abandoned Soils of European Russia in 1990–2020

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Abstract—Experimental studies and the analysis of published data have shown that carbon reserves in soils generally increase upon soil exclusion from agricultural use. The rate of carbon accumulation in the abandoned soils depends on the soil type, the time elapsed since the soil abandoning (the restoration period), and the thickness of the layer for which the rate of carbon accumulation is determined. For the upper 20-cm-thick layer, it varies from 66 to 175 g C/m^2 per year in dependence on the type of soil and averages 111 g C/m^2 per year. The highest rate is typical of the first 10–15 years of soil restoration. According to our calculations, the carbon sequestration in the upper 20-cm-thick layer of Russian soils due to changes in land use was 184–673 Mt C in 1990–2005 and may reach 282–1030 Mt C by 2020.

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INTRODUCTION

The changes in the total pool of soil organic carbon (SOC) are controlled by the ratio between the organic matter (OM) input and the intensity of its decomposition (mineralization) [11, 22, 44]. The rate of the OM mineralization depends on the amount and quality of the plant residues [6, 17, 19, 32, 33], the soil type, the soil texture [16], and the soil water and temperature regimes [23, 25, 29–31, 39]. The reserves of SOC in natural ecosystems are relatively stable; changes in land use lead to quantitative and qualitative transformation of soil OM until a new equilibrium is achieved [11, 36, 43, 45].

The most important processes leading to accumulation of the SOC are as follows: (1) an increase in the amount of OM entering the soil, (2) an enrichment of deep soil layers with OM due to the rise in the amount of below-ground phytomass and its more active mixing by soil fauna, and (3) the development of organomineral complexes protecting the OM from microbial decomposition [11, 34, 35, 40]. Favorable conditions for these processes are usually created after abandoning of plowlands. Plant material is not removed from the field upon harvesting, perennial vegetation is restored, and carbon is accumulated in the soils and plants [18, 20, 21, 24, 27, 37, 38, 41, 46]. In addition, the residence time of the SOC increases, and the humus content in the soil profile becomes significantly higher. Published data on the rates of carbon accumulation in different soil types upon changes in land use are summarized in [35]. The rates of carbon accumulation in the formerly cultivated soils converted into meadow ecosystems and pastures vary from 3.1 to 113.5 g C/m^2 per year with respect to the bioclimatic zone and the thickness of the soil layer taken into account; the average rate is estimated at 33.2 g C/m^2 per year. Upon the restoration of forest vegetation on the formerly plowed soils, the average rate of carbon accumulation is similar (33.8 g C/m^2 per year). When traditional tillage is replaced by no-till practices, the rate of carbon sequestration becomes even higher (57 ± 14 g C/m^2 per year) [45]. In our work, we tried to (1) determine the rates of carbon sequestration in formerly cultivated soils after their abandoning in dependence on the thickness of the soil layer and the time after the soil abandoning and (2) assess the total amount of organic carbon sequestered in the soils of Russia in 1990–2005 under the impact of the changes in the land use system.

OBJECTS AND METHODS

A database on changes in the carbon reserves in the soils of the Russian Federation upon natural revegetation and upon human-controlled afforestation of formerly plowed lands was developed [1, 2, 7–10, 14, 26, 28]. Its analysis demonstrated that the published data are fragmentary, the investigated soils are not numerous, and the restoration period is about several decades. In addition, the thickness of the soil layer taken into account upon calculation of the carbon reserves varied from 10 to 100 cm. In order to unify and specify the available data, we performed additional investigations of the main soil types in Russia: soddy-podzolic (Vladimir oblast), gray forest (Moscow oblast), ordinary chernozem (Rostov oblast), and chestnut soils (Volgograd oblast).[1] To obtain more adequate estimates of the

[1] In 1990, these soil types comprised about 85% of all the agricultural lands in Russia.

Table 1. Average rates of carbon accumulation (±SE, g C/m^2 per year) in the upper 20-cm-thick layer of the main soil types as dependent on the duration of the self-restoration period

Soil	Self-restoration period		
	1–15 years	1–30 years	1–77 years
Soddy-podzolic	131 ± 13	111 ± 22	97 ± 22
Gray forest	134 ± 36	105 ± 26	102 ± 23
Chernozem	175 ± 52	152 ± 44	109 ± 32
Chestnut	66 ± 24	Not det.	
Total soil sequence	132 ± 21	111 ± 16	99 ± 14

organic carbon pools and the rates of carbon sequestration in gray forest soils and chernozems, two succession chronosequences were studied on these soils. They included the plowed soils and the soils with different restoration periods: 2, 6, 11, and 26 years on gray forest soils and 5, 11, 21, and 77 years on ordinary chernozems. The soil samples for determining the organic carbon content were taken from each 10-cm-thick layer to a depth of 50–60 cm. To estimate the organic carbon pools and the rates of carbon sequestration, the soil bulk density was determined at the same depths. We failed to find analogous chronosequences for soddy-podzolic and chestnut soils. For soddy-podzolic soils, a plowed variant and a 12-year-old fallow were studied; for chestnut soils, a plowed variant and a 15-year-old fallow were studied. The organic carbon content was only determined in the plow horizon (0–20 cm) of the soddy-podzolic soil. In the chestnut soil, it was determined in each 10-cm-thick layer to a depth of 50 cm. The method of Tyurin in modification of Nikitin (the method of bichromate oxidation with spectrophotometric ending) was applied to determine the organic carbon content. The organic carbon pool (S_C, g C/m^2) in the soil layer of thickness H (m) was calculated from data on the organic carbon content in the same layer (C_C, g C/100 g of soil) and the soil bulk density (BD, g/cm^3) according to the following equation:

$$S_C = C_C \times BD \times H \times 10^4. \quad (1)$$

The rate of carbon accumulation (Cac, g C/m^2 per year) in a soil during the restoration period D was calculated from the difference in the carbon pools of the revegetated (RS_C) and plowed (AS_C) soils. The carbon state of the plowed soils was taken as the zero moment. The obtained difference was divided by the number of years (D) elapsed since the soil abandoning:

$$Cac = (RS_C - AS_C)/D. \quad (2)$$

RESULTS AND DISCUSSION

The dependence of the rate of carbon accumulation on the soil type and the period of self-restoration. According to the results of our investigations on fallow fields of different ages in different bioclimatic zones and the database developed from published data, the rate of carbon accumulation in the former plow layer (0–20 cm) varies from 4.2 to 484 g C/m^2 per year and averages up to 99 ± 14 g C/m^2 per year. As seen from Table 1, it depends on the type of soil and the duration of the restoration period. It is usually higher within the first years of the soil restoration (1–15 years) and drops considerably within several decades. The average rates of carbon accumulation in the upper 20-cm-thick layer within the first 15 years for soddy-podzolic, gray forest, chernozemic, and chestnut soils are 131, 134, 175, and 66 g C/m^2 per year, respectively. The obtained data make it possible to assume that the rate of carbon accumulation in the former plow layers increases with an increase in the humus content in them and is the highest in chernozems. The dependence of the rate of carbon accumulation on the duration of the restoration period for particular soil types (soddy-podzolic, gray forest, and chernozemic soils) is shown in Fig. 1. There is a pronounced negative logarithmic correlation between the rate of carbon accumulation and the duration of the soil restoration period. The determination coefficients (R^2) in the equations are rather high (0.71–0.89).

The rates of carbon accumulation calculated by us for the main soil types of the European part of Russia are in agreement with the data obtained by other authors. Post and Kwon have found that the maximum rate of carbon accumulation is typical of the early stages of soil restoration, though it does not exceed 100 g C/m^2 per year [35]. Upon restoration of forest vegetation on the former croplands in the tropical zone, the rate of carbon accumulation reaches 130 g C/m^2 per year within the first two decades and is 41 g C/m^2 per year in the following 80 years [42]. Similar conclusions are made in [45]. The authors have shown that the substitution of no-till practices for traditional tillage results in the increasing sequestration of carbon with a maximum between the fifth and tenth year; the new system reaches an equilibrium status in 15–20 years. The average rate of carbon accumulation calculated via comparing 276 pairs of plots with different cultivation systems is 57 ± 14 g C/m^2 per year.

Conversion coefficients for recalculation of the rates of carbon accumulation. The analysis of published data has shown that the rate of carbon accumulation is usually determined for the upper 20–60 cm; sometimes, only the uppermost 10-cm-thick soil layer is investigated [8]. The most pronounced changes in the carbon reserves occur in the upper 20-cm-thick layer (the former plow horizon) and in the upper 30-cm-thick layer. At the late stages of soil restoration (after settling of shrubs and trees), these changes also affect the deeper soil horizons [21].

We have experimentally determined the reserves of organic carbon and the rates of carbon accumulation in the particular layers of chernozemic, gray forest, and chestnut soils. The obtained data make it possible to suggest conversion coefficients for calculating the rates of carbon accumulation (Cac) in the 20- and 30-cm-thick layers of the restoring soils from data on the uppermost 10-cm-thick soil layer (Table 2).

The coefficients for recalculating the Cac in the upper 10 cm into the Cac in the upper 20 cm vary from 1.00 to 2.21 and are usually 1.5–2.5 times higher as compared with the coefficients for recalculating the Cac in the upper 20 cm into the Cac in the upper 30 cm. The average conversion coefficients for the Cac are 1.57 for the transition from the layer of 0–10 cm to the layer of 0–30 cm and 1.04 for the transition from the layer of 0–20 cm to the layer of 0–30 cm. The highest rates of carbon accumulation in gray forest soils are typical of the upper 20-cm-thick layer.[2] In chernozems and chestnut soils, where the humus accumulation is more active and is developed in deeper soil layers, the rates of carbon accumulation are the highest in the 30-cm-thick layer. Thus, our investigations have proved the effect of the zonal factor dictating the predomination of particular soil-forming processes on the rates of carbon accumulation in soils.

Assessment of the rates of carbon accumulation upon afforestation of former croplands. The above-discussed approach is valid for soils that have undergone natural succession processes after their exclusion from agricultural use due to the new economic policy in Russia in the early 1990s. The natural vegetation succession on abandoned fields proceeds from the stage of weeds (the first 4–5 years) to the stage of typical meadow plants with self-seeding of different trees (birch and pine on podzolic and gray forest soils, and acacia and apricot trees on chernozems). In order to estimate the changes in the SOC upon human-controlled afforestation, we used published data [8] and the results of our investigations. Data on the carbon content in cultivated soils and in the soils under tree plantations (shelterbelts) of different ages were taken from [8]. The age of the studied forest strips varied from 22 to 50 years, and they were allocated to different bioclimatic zones with gray forest, chernozemic, and chestnut soils and solonetzes. Only the upper 10-cm-thick soil layer was studied. In order to estimate the reserves of organic carbon and calculate the rates of carbon accumulation under forest plantations, the values of the soil bulk density for plowed soils and for soils under natural vegetation in different soil-climatic zones given in the work by Titlyanova [15] were used. Taking into consideration these data and the conversion coefficients obtained by us (Table 2), we calculated the average rates of carbon accumulation in the layers of 0–10, 0–20, and 0–30 cm for the soils of different types under artificially planted forests of various ages (Table 3).

[2] In the investigated sequence of gray forest soils, fallow plots abandoned 2, 6, and 26 years ago were allocated to eroded areas. That is why the rate of carbon accumulation in the 30-cm-thick layer was lower than that in the 20-cm-thick layer.

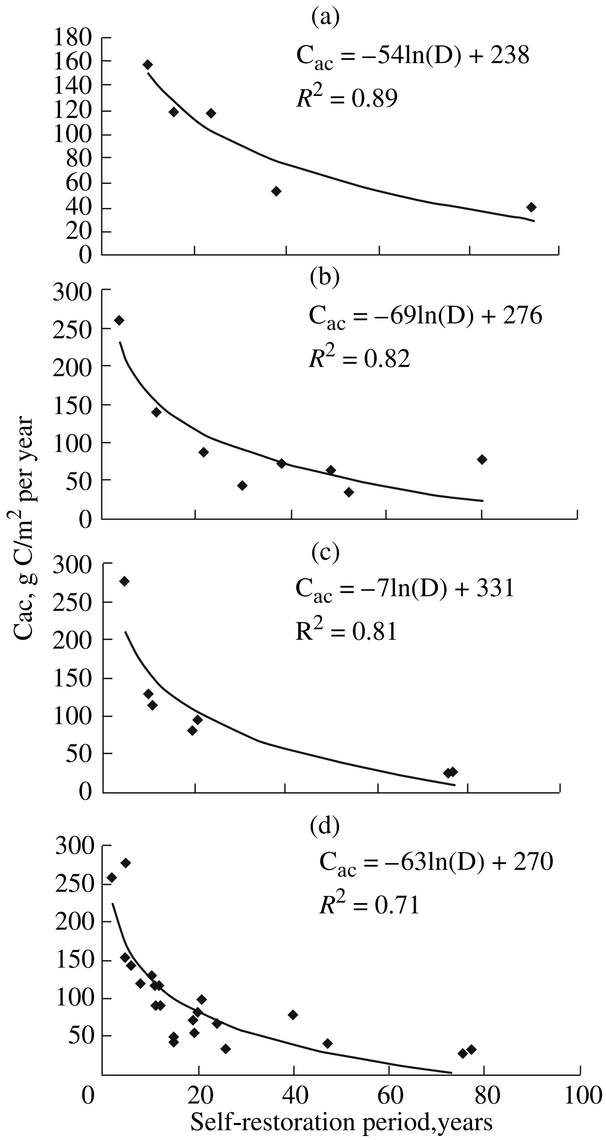

Fig. 1. The rates of carbon accumulation (Cac, 0–20 cm) as dependent on the duration of self-restoration of vegetation (D) on the formerly cultivated (a) soddy-podzolic, (b) gray forest, and (c) chernozemic soils; (d) the same for the entire range of studied soils.

As seen from these data, the rates of carbon accumulation in the upper 10-cm-thick soil layer under forest plantations vary from 21 to 72–79 g C/m^2 per year. The mean Cac values calculated for the particular soil types do not differ reliably; however, according to them, the studied soils can be arranged into the following sequence: chestnut soils and solonetzes (56 g C/m^2 per year) > gray forest soils (44 g C/m^2 per year) > chernozems (38 g C/m^2 per year). The species composition of the trees in forest strips (shelterbelts) and their age exert a slight effect on the Cac in the upper 10-cm-thick layer. For deeper soil layers, an inverse relationship between the Cac and the age of the forest strips is observed: the average Cac is 66–76 g C/m^2 per year for

Table 2. Conversion coefficients for calculating the rates of carbon accumulation in different soil layers

Soil	Restoration period, years	Accumulation rate, g C/m^2 per year			Conversion coefficients		
		0–10 cm	0–20 cm	0–30 cm	0–20/0–10 cm	0–30/0–10 cm	0–30/0–20 cm
Gray forest	2	129	259	141	2.00	1.09	0.54
	6	73	143	138	1.96	1.90	0.97
	11	49	90	94	1.82	1.90	1.04
	26	23	35	31	1.54	1.36	0.88
	Mean	**69**	**132**	**101**	**1.83**	**1.56**	**0.86**
Ordinary chernozem	5	126	279	283	2.22	2.25	1.02
	11	63	117	148	1.86	2.34	1.26
	21	60	98	114	1.64	1.91	1.16
	77	21	30	33	1.46	1.58	1.08
	Mean	**67**	**131**	**144**	**1.79**	**2.02**	**1.13**
Chestnut	15	42	42	39	1.00	0.93	0.93
	12	90	90	110	1.00	1.22	1.22
	Mean	**66**	**66**	**75**	**1.00**	**1.13**	**1.13**
All soils	General mean	**67**	**110**	**108**	**1.54**	**1.57**	**1.04**

Table 3. Average rates of carbon accumulation (±SE, g C/m^2 per year) in different soil layers under forest plantations with respect to their age and the soil type

Soil layer, cm	Soil type				Age of forest plantations, years			General mean
	Gray forest	Chernozem	Chestnut	Solonetz	20–30	30–40	40–50	
0–10	44 ± 14	38 ± 4	55 ± 7	56	46 ± 7	41 ± 7	45 ± 7	44 ± 4
0–20	81 ± 26	69 ± 8	55 ± 7	56	72 ± 15	66 ± 9	60 ± 4	66 ± 6
0–30	69 ± 22	78 ± 9	63 ± 8	63	76 ± 16	74 ± 10	66 ± 6	72 ± 6

20- to 40-year-old forest strips and 60–66 g C/m^2 per year for older forest strips (Table 3). The effect of the soil type on the rate of carbon accumulation is well pronounced for the layers of 0–20 and 0–30 cm. Maximum Cac values are typical of the layer of 0–20 cm in gray forest soils and of the layer of 0–30 cm in chernozems. The average Cac values for the 20- and 30-cm-thick soil layers under forest plantations on the formerly cultivated soils are 66 ± 6 and 72 ± 6 g C/m^2 per year, respectively. It should be mentioned that the obtained data characterize the rates of carbon accumulation under well-developed tree plantations with an age of more than 20 years. Under younger forests, the rates of carbon accumulation may be two–three times higher.

A comparative analysis of the rates of carbon accumulation in the 20- and 30-cm-thick soil layers upon natural vegetation successions and upon artificial planting of trees on former croplands shows that they are approximately similar for the soils of similar geneses. Therefore, a unified database can be used to calculate the rates of carbon accumulation in the abandoned agricultural soils upon their overgrowing with natural vegetation and upon their purposeful afforestation. The mean rate of carbon accumulation in the upper 20-cm-thick soil layer during the first 15 years of soil restoration is 132 ± 21 g C/m^2 per year. In soils with a longer restoration period (16–30 years), the mean rate of the carbon accumulation rate is almost two times lower (72 ± 9 g C/m^2 per year). Figure 2 displays the relationship between the rates of carbon accumulation in the 20- and 30-cm-thick soil layers and the duration of the soil restoration. These data have been obtained from the analysis of 41 pairs of plots on the cropland and on the abandoned (or afforested) soils. The obtained relationships can be approximated by an inverse logarithmic function with high reliability (R^2 = 0.45–0.60, $F < 0.001$); they make it possible to calculate the rates and volumes of the carbon accumulation in the former plow layer and in the 30-cm-thick soil layer for different time periods.

Assessment of changes in the reserves of carbon in the soils of the Russian Federation in 1990–2020. Changes in the economic policy of Russia in the early 1990s resulted in a considerable decrease in the area of plowed lands. According to different estimates, the

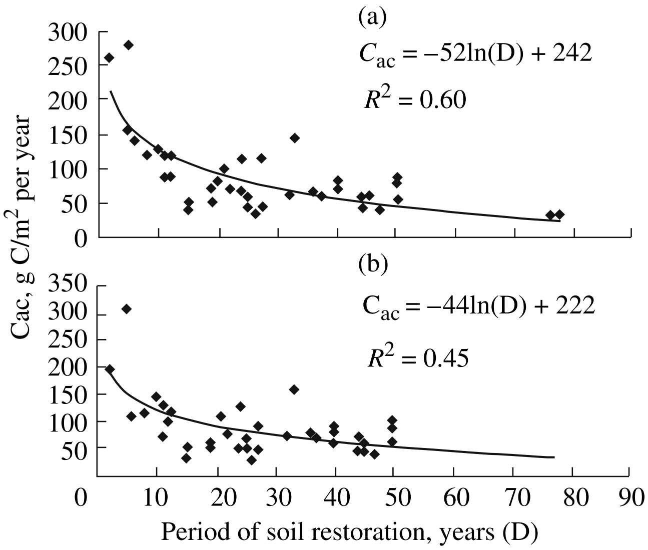

Fig. 2. The rates of carbon accumulation in the layers of (a) 0–20 cm and (b) 0–30 cm as dependent on the length of the restoration period (from data on 41 paired plots).

total plowed area excluded from agricultural use within the last 10–15 years varies considerably. The data of FAO UNESCO suggest that the area of plowed lands in Russia decreased by 9.3 million ha in 1990–2003. The Russian Statistical Department estimated this decrease at 14.3 million ha for the same period on the basis of Land Cadastre of Russia reports [3]. According to Pankova and Novikova, the area of plowed lands excluded from agriculture in 1990–1995 comprised 34 million ha (1/3 of the plowed area) [12]. Similar data are given in [4]: 32 million ha (27%) of lands were excluded from cultivation in 1985–2003. The areas of fallow calculated in [13] and [5] are smaller: 21.6 million ha in 1990–2002 and 29 million ha (1/4) in 1990–1999, respectively.

The total accumulation of organic carbon in soils of the Russian Federation as a result of changes in land use was roughly estimated for an area of 34 million ha at 660 Mt of C (for the period from 1990 to 2002) [28]. The total accumulation of organic carbon in abandoned soils of the former Soviet Union calculated with the use of the Orchid model is 116–131 Mt of C for 1993–2000 and 214 Mt of C for the next decade (2000–2010). In the work of Romanovskaya [13], the carbon sequestration in the abandoned soils of Russia was estimated with the use of the RothC model. The author pointed to the loss of carbon (5.5 Mt of C) from fallow lands of Russia within the first 13–15 years of soil restoration (1990–2002) [13]. According to our data, the average rate of carbon sequestration in the former plow layer within the first stages of soil restoration is 132 ± 21 g C/m^2 per year (for the first 15 years). Thus, the total accumulation of organic carbon in the abandoned soils of Russia in 1990–2005 could reach 184–673 Mt of C (for the upper 20 cm). If we assume that no significant changes in the area of plowed soils of Russia will take place in the next 15 years, the additional carbon accumulation by 2020 can be 98–357 Mt of C. The considerable variability of the obtained estimates is due to the uncertain determination of the area of plowed lands excluded from agricultural use since 1990.

CONCLUSIONS

Changes in the economic policy of Russia in the early 1990s have resulted in a considerable decrease in the area of agricultural lands. The development of perennial vegetation on the former croplands has led to active soil restoration processes accompanied by carbon sequestration. The experimental study and the analysis of published data have shown that the rate of organic carbon accumulation in the abandoned soils depends on the soil type, the thickness of the soil layer taken into account in the corresponding calculations, and the period for which the rate of carbon accumulation is calculated. Chernozems with a deeper humus layer (as compared with gray forest and chestnut soils) are characterized by a higher accumulation of carbon in the upper 30-cm-thick layer. The rate of carbon accumulation decreases with an increase in the age of artificially planted forests on former croplands or the duration of the natural self-restoration period. The highest rates of carbon accumulation are typical of the first 10–15 years of the soil restoration and average up to 132 ± 21 g C/m^2 per year in the upper 20-cm-thick layer. After 15 years of restoration of meadow or forest vegetation on abandoned croplands, the rate of carbon sequestration decreases and does not exceed 70 ± 8 g C/m^2 per year. According to our calculations, the total amount of organic carbon accumulated in the upper 20-cm-thick layer of Russian soils due to changes in land use was 184–673 Mt of C in 1990–2005 and will reach 282–1030 Mt of C by 2020. The considerable variability in the obtained data is mainly explained by the uncertainty of the available estimates of the areas of soils excluded from cultivation since 1990. Signing of the Kyoto Protocol by Russia in 2004 makes such estimates especially actual.

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