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SOIL CHEMISTRY

The Rates of Organic Matter Renewal in Gray Forest Soils and Chernozems

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Abstract—The rates of soil carbon renewal were determined by the method of natural ^{13}C abundance in a chernozem under a 40-year-long monoculture of corn and in a gray forest soil after application of corn residues. The mean rate of soil carbon renewal in the chernozem reached 1271–1498 years, whereas in the gray forest soil it depended on the amount of carbon introduced with corn residues and varied from 19 to 63 years. The rate of organic carbon renewal in the chernozem decreased from 697 years in the upper horizon to 2742 years in the layer of 40–60 cm. The mean residence time of organic carbon generally increased with a decrease in the size of particle-size fractions.

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INTRODUCTION

Soil is the main reservoir of organic carbon in terrestrial ecosystems; carbon preservation in soil humic substances for a long time is an important factor regulating the gas composition of the atmosphere [18]. Information about the rate of carbon turnover in Russian soils is necessary for predicting consequences of the global climate change. Along with data on the total amount of carbon stored in soils, information on the size and time of renewal of labile and stable pools of soil organic matter, the intensity of humification of plant residues, and the mechanisms of organic matter stabilization in soils is necessary for understanding the carbon turnover under changing environmental conditions.

The method of natural abundance of ^{13}C isotope in the case of substitution of C_4 plants for C_3 plants, e.g., upon growing of C_4 corn ($\delta^{13}C$ = 12–14 ‰) as a monoculture on a soil, on which C_3 plants ($\delta^{13}C$ = 26–27‰) grew earlier [9], makes it possible to estimate necessary characteristics of carbon turnover in agrocenoses, ecosystems with the most dynamic balance of soil organic matter. The method of natural ^{13}C abundance in the case of replacement of C_3 to C_4 plants characterizes a relatively labile pool of soil carbon with the mean residence time from several tens to several hundreds of years [12, 17]. The resistance of this pool to destruction under conditions of varying soil temperature and moisture is of great importance relative to the greenhouse effect, because climate changes are usually forecasted for a period of 50–100 years [18], i.e., within the range of the labile pool renewal. This approach has not found wide application in Russia because of the predominance of C_3 plants on its territory. In this study, we tried to evaluate the rate of carbon turnover in the leached chernozem under the monoculture of corn. As there was no the substitution of C_4 plants for C_3 plants on the gray forest soil under natural conditions, the rates of carbon turnover in this soil were estimated on the basis of microplot experiments on the destruction of corn residues in the soil.

Investigation into the mechanisms of stabilization of soil organic carbon that may mitigate the greenhouse effect assumes the separation of soil organic matter into labile and stabile pools. The microbial biomass and free organic substances and half-decomposed plant residues with low density (so-called light fractions) are usually classified as labile components [3, 17]. Organic compounds, mostly specific humic substances firmly bound with the mineral part of soil, are considered stable components. The method of particle-size–density fractionation—a combination of the methods of particle-size and particle-density fractionation—is used to separate free and firmly bound organic components. Stable organomineral complexes are associated with the fine silt and clay particle-size fractions, whereas labile free components are isolated with the help of density fractionation in heavy liquids [3, 7, 11, 17, 20]. The fractions isolated with the help of the particle-size–densitometric analysis are heterogeneous in their composition and the rates of their renewal in soil. Light-weight fractions include not only labile components but also thermodynamically stable humic substances represented by the complexes of metals with humic acids [3] and by difficultly decomposable carboniferous components [17]. At the same time, fine silt and clay fractions include polysaccharides of predominately microbial origin additionally to stable complexes of clay minerals, oxides, and hydroxides with humic substances [3, 16].

We suppose that a combination of the method of natural ^{13}C abundance in the case of replacement of C_3 by C_4 plants and the method of particle-size–density fractionation makes it possible to separate more homogeneous fractions (with respect to the rates of the organic matter decomposition) than each of these methods taken alone. Determination of the content of young organic carbon of C_4 origin in light fractions allows us to separate the labile component; the same method applied to heavy (silt and clay) fractions makes it possible to assess the contribution of labile admixtures to the stable organomineral soil components.

Our work was aimed at determining the rates of carbon turnover in the soil organic matter and in the particular particle-size–density fractions isolated from arable gray forest soils and leached chernozems via comparing the isotopic composition of organic matter in the case of substitution of C_4 plants for C_3 plants with the initial ^{13}C abundance factor.

OBJECTS AND METHODS

The study was performed in 2000–2005 on the gray forest soil (C_{org} 1.1%, pH_{KCl} 4.65) at the Experimental Station of the Institute of Physicochemical and Biological Problems of Soil Science of the Russian Academy of Sciences in Pushchino (Moscow oblast) and in 2006 on the leached chernozem (C_{org} 3.2%, pH_{KCl} 5.3) on experimental plots of Voronezh Branch of the All-Russia Research Institute of Corn.

The rate of carbon turnover in the gray forest soil was determined in a microplot experiment established on a fallow field. For this study, ground residues of green corn were added into the upper 25-cm-thick soil layer during five years in the fall seasons at the rates of 1.0 and 3.0 kg/m^2 (dry matter equivalent), which corresponded to the input of 1.9 and 5.8 kg C/m^2 over the whole period, respectively. The first value corresponded to the amount of organic carbon entering the soil with plant remains and manure in the case of intensive agriculture; the second value corresponded to the input of organic carbon into the soil under highly productive meadow communities. The C/N ratio in the initial soil was 27. The experimental plots were of 1 m^2 in area; the experiment was performed in duplicate. Experimental plots were isolated with rigid PVC sheet frames inserted into the soil to a depth of the plow layer; wooden grates preventing the soil drying were placed on the top. The soil was tilled every fall in order to mix the introduced plant remains with the mineral soil mass; the spring tillage was aimed at the soil loosening and maintaining the fallow state. The soil water content in the 25-cm layer during the growing season varied from 17 to 25% in all the years of the experiment. The soil samples were taken from the layer of 0–25 cm after completing the experiment at every plot from 5 points, and the composite samples were obtained.

In the chernozem, soil samples were taken under the 40-year-old monoculture of corn from 20-cm-thick layers to a depth of 100 cm. We studied control plots without fertilization and a variant with complete mineral fertilizer N120P60K60. The experiment was performed in triplicate. The samples were also taken in 5 points on each of the plots, and composite samples were prepared.

The soil mass was fractionated with the method of dry sieving [2]. Separate weighing portions were subjected to the particle-size fractionation. For this purpose, 50 g of air-dried soil were mixed with water in the amount of 25% from the soil weight and dispersed with the help of 30-min grinding. Then, the soil paste was sieved through sieves 1 to 0.1 mm mesh. The fraction <0.1 mm was treated with ultrasound of sound power 100 W during 15 min and separated to particle-size fractions by the method of elutriation in water [2]. After exhaustive extraction, the fractions were settled down by centrifuging during 30 min at 400 rpm (1600 g) in a centrifuge K-70. In the chernozem, coarse fractions (coarse sand >250 μm and fine sand <250 μm) also contained the light fraction that was separated with the help of flotation in water. In the gray forest soil, coarse fractions were not separated into organic and mineral components.

Organic carbon and nitrogen were determined in the bulk soil samples and in the isolated fractions, and concentrations of heavy isotope ^{13}C were determined on a mass-spectrometer MAT 253 (Thermo, Finnigan, Germany) with element analyzer Euro EA (Eurovector, Italy). Analytic signal for isotope ^{13}C was expressed in $\delta^{13}C$ units relative to the international VPDB standard:

$$\delta^{13}C = (R_{sam}/R_{stand}) - 1, \qquad (1)$$

where R_{sam} and R_{stand} are the ratios $^{13}C/^{12}C$ in the sample and in the standard, respectively. The $\delta^{13}C$ value for VPDB equals 0‰.

Simultaneously, we determined the isotope composition of the green mass of corn introduced into the gray forest soil, and concentrations of ^{13}C in the underground mass and stubble of corn grown on the chernozem: $\delta^{13}C$ comprised 13.7 and 11.6‰, respectively. The long-term data on corn productivity were used to calculate the amount of carbon introduced into the soil in the course of 40-year-long cultivation of corn in monoculture [5].

Before the determination of the isotopic composition of carbon in separate particle-size fractions of chernozem, the latter were freed from carbonates with 0.05 N HCl until negative reaction for Ca^{2+} ions [1].

Table 1. Pools and mean residence times of organic matter in the chernozem and gray forest soil

Variant	C_{org}, kg C/m^2	C–C_4, kg C/m^2	MRT, years	Input of corn residues, kg C/m^2	Humification coefficient, K_h, %
	0–100 cm				
Chernozem, 40-year-old corn monoculture					
Initial soil	24.8 ± 2.4	0	Not det.	Not det.	Not det.
Control	27.2 ± 4.1	0.75 ± 0.14	1271 ± 37	7.7 ± 1.1	9.7 ± 0.6
N120PK	28.6 ± 8.3	0.84 ± 0.25	1498 ± 30	11.8 ± 2.6	7.1 ± 0.7
Gray forest soil, 5-year-long input and decomposition of corn residues					
Control	6.81 ± 0.11	0.52 ± 0.08	63.3 ± 2.5	1.9	27.4 ± 2.1
Control	7.7 ± 0.18	1.78 ± 0.28	19.0 ± 1.2	5.8	30.7 ± 2.3

The portion of C_4 carbon of corn in the soil was calculated according to the following equation:

$$\delta^{13}C_s = f\delta^{13}C_4 + (1 - f)\delta^{13}C_3, \quad (2)$$

where $\delta^{13}C_s$ is $\delta^{13}C$ in the soil sample; $\delta^{13}C_4$ is $\delta^{13}C$ in the fresh organic matter forming upon the decomposition of corn residues; $\delta^{13}C_3$ is the content of heavy isotope ^{13}C in the initial soil samples taken before the establishment of the experiment in 1966; and f is the portion of organic matter of C_4 origin, i.e., the portion of newly formed humus accumulated in the soil during the last four decades under the monoculture.

The constant of decomposition (k) and the mean residence time (MRT) of soil organic matter were calculated on the basis of an assumption that the decomposition of plant residues proceeds according to the exponential law [9]:

$$k = \ln(1 - f)/t, \quad (3)$$

$$\text{MRT} = 1/k. \quad (4)$$

The results of analyses were calculated per absolutely dry weight.

RESULTS AND DISCUSSION

Data on carbon reserves in the leached chernozem (Table 1) suggest the high stability of soil organic matter: the amounts of carbon in the soil prior to corn growing, in the not fertilized control, and in the variant with NPK fertilization under the 40-year-old monoculture of corn did not differ significantly. Carbon that entered the soil from C_4 corn plants was accumulated in the soil to a depth of 60 cm. A significant change in the isotopic composition of soil organic carbon in comparison with the initial samples was not observed in the soil layers of 60–80 and 80–100 cm. The maximum accumulation of carbon of C_4 origin comprised no more than 5.6% of the total amount of organic carbon in the upper soil horizon (Table 2). The obtained rate of carbon renewal is much lower than the values reported by other authors. Normally, the growing of corn for 30–40 years results in the renewal of soil organic matter by 23–40% in the upper horizons and by 4–15% at a depth of 50–100 cm [12]. In the soil not subjected to tillage, the amount of renewed carbon may reach 90% [19]. It can be assumed that such a low rate of carbon renewal in our experiment is due to the high carbon content in the chernozem and the low productivity of corn grown in monoculture. The productivity of corn, as well as the input of postharvest corn residues into the soil, is actually 1.5 times higher in the case of its use in the ten-course rotation than in the monoculture. However, taking into account the high productivity of corn in comparison with other crops, the average input of plant residues into the soil in the crop rotation and in the monoculture do not differ significantly [5]. Hence, the great store of carbon in the soil is the main reason for the slow rate of its renewal in the chernozem.

The MRT of organic matter in the chernozem gradually decreased down the soil profile and reached 697 and 2742 years in the layers of 0–20 and 60–80 cm, respectively (Table 2). The MRT of carbon in the gray forest soil was significantly lower: 19 to 63 years (Table 1). It was comparable with the values obtained earlier with the method of natural ^{13}C abundance in the case of changes in the type of vegetation (C_3–C_4 plants) for other types of soils and ecosystems [4, 9, 12, 16, 19]. The MRT of organic matter in the soils decreased almost parallel to an increase in the input of new plant residues. These data make it possible to suppose that the substitution of perennial plants for annual crops (i.e., the conversion of a cropland into a meadow) should result not only in the significant rise in the reserves of soil organic matter but also in the increasing rate of the soil organic matter renewal.

Table 2. Rates of organic carbon renewal at different depths of the leached chernozem

Depth	C_{org}, kg/m^2	C–C_4/C_{org}, %	MRT, years
0–20	8.8 ± 2.2	5.6 ± 0.4	697 ± 57
20–40	7.2 ± 0.9	3.7 ± 0.2	1063 ± 26
40–60	6.1 ± 0.6	1.4 ± 0.3	2742 ± 35

Table 3. Carbon distribution by the fractions of dry sieving in the gray forest soil

Input with corn residues, kg C/m^2	Fraction, mm	Mass, %	C_{org}, %	C/N	$C–C_4/C_{org}$, %	MRT, years
1.9	>5	50.8	1.5	9.2	11.4	41.2
	5–3	21.9	1.4	9.8	11.3	41.9
	3–2	12.8	1.5	10.0	11.9	39.6
	2–1	5.1	1.5	10.4	11.7	40.0
	1–0.5	3.5	1.5	10.2	12.4	37.8
	0.5–0.25	2.6	1.6	10.3	13.7	33.9
	0.25–0.1	1.8	1.7	10.2	15.6	29.5
	<0.1	1.5	1.2	10.1	12.4	37.9
5.8	>5	41.5	1.9	10.2	32.6	12.7
	5–3	22.8	1.8	10.6	30.8	13.6
	3–2	13.5	1.8	10.5	31.1	13.4
	2–1	8.6	1.9	10.9	31.3	13.3
	1–0.5	4.8	1.9	10.8	30.8	13.6
	0.5–0.25	3.9	2.0	10.9	37.0	10.8
	0.25–0.1	2.5	2.2	11.1	38.2	10.4
	<0.1	2.4	1.4	10.6	29.3	14.4

Unlike the rate of organic matter renewal, the coefficient of humification (K_h) of corn residues in the chernozem studied by us was in agreement with previously obtained values. The values of this coefficient did not differ significantly in the fertilized and control variants (7.1 and 9.7% respectively). In a series of long-term experiments with corn monoculture in the United States, Collins et al. [12] determined that the coefficient of humification varied from 5.5 to 16.6%, and 47% of the variation were associated with the duration of corn growing in monoculture. In our experiments, K_h was significantly higher in the gray forest soil than in the chernozem (Table 1) and did not depend on the amount of plant residues entering the soils. The observed difference between these soils was probably due to different duration of the experiments: K_h decreased with an increase in the time of growing of C_4 plants in agreement with the exponential law of decomposition of plant residues (Eq. 4).

Fractionation of gray forest soil with the help of dry sieving did not allow us to isolate components differing significantly in the concentration of organic carbon and the renewal rates of organic carbon of C_4 origin (Table 3). Fractionation by the method of dry sieving is the least destructive method of soil fractionation, but isolated components did not differ in their characteristics from the bulk soil mass.

Determination of the total and labeled carbon in particle-size fractions of both soils attests to the separation of organic matter to the components with contrasting contents and isotopic composition of organic carbon (Tables 4, 5). The high content of total carbon in the largest particles in the gray forest soil was due to the admixture of light fraction in sandy particles. In the chernozem, the separation of light fraction from sand particles by the flotation method showed that the concentration of organic carbon in the light fraction was 5–10 times higher than that in the mineral components (Table 5). The predominant fraction of coarse silt was characterized by the minimum content of carbon; the concentration of organic carbon in finer fractions increased with a decrease in the size of particles. The maximum concentration of organic carbon was detected in the clay fraction from the gray forest soil (Table 4) and in the fine silt fraction from the chernozem (Table 5).

The C/N ratio in the fractions of gray forest soil decreased with a decrease in the size of particles: from 11–15 in coarse fractions to 8.3–8.6 in clay particles (Table 4). In the chernozem, this relationship had a more intricate pattern (Table 5). By and large, the C/N ratio was higher in coarser fractions. The C/N ratio differed most significantly between the light-weight organic and mineral components of the coarse fractions: it was higher in the light organic fractions in comparison with the mineral fractions of the same size, which attests to similar compositions of light fractions and plant residues.

The content of young carbon of C_4 origin in the fractions of gray forest soil (Table 4) depended on two factors: the amount of plant residues and the fraction size. The portion of C_4 carbon in the fractions increased with an increase in the amount of introduced corn residues and decreased with a decrease in the size of the frac-

Table 4. Carbon distribution by the particle-size fractions of gray forest soil (mean ± standard deviation)

Input with corn residues, kg C/m^2	Fraction, μm	Mass, %	C_{org}, %	C/N	$C–C_4/C_{org}$, %	MRT, years
0	Sand + LF*, 100–1000	2.9	1.6 ± 0.15	10.8 ± 0.2		
	Coarse silt, 10–100	58.0	0.4 ± 0.04	11.1 ± 0.6		
	Medium silt, 10–5	5.6	1.8 ± 0.05	10.9 ± 0.03		
	Fine silt, 1–5	10.0	3.2 ± 0.2	9.8 ± 0.3		
	Clay, <1	9.8	4.1 ± 0.05	8.3 ± 0.05		
1.9	Sand + LF*, 100–1000	8.4	3.4 ± 0.05	13.9 ± 0.3	34.0 ± 0.1	12.1 ± 0.04
	Coarse silt, 10–100	56.6	0.5 ± 0.13	12.0 ± 1.0	21.8 ± 1.0	20.4 ± 1.0
	Medium silt, 10–5	5.4	1.6 ± 0.15	11.3 ± 0.01	15.1 ± 0.1	30.7 ± 0.2
	Fine silt, 1–5	12.6	3.5 ± 0.2	10.3 ± 0.05	8.1 ± 0.1	59.4 ± 0.7
	Clay, <1	8.6	4.5 ± 0.37	8.5 ± 0.06	7.6 ± 0.1	63.0 ± 0.8
5.8	Sand + LF*, 100–1000	6.2	5.1 ± 0.6	15.0 ± 0.5	68.9 ± 0.8	4.3 ± 0.3
	Coarse silt, 10–100	56.6	0.6 ± 0.1	12.3 ± 1.4	45.1 ± 0.2	8.4 ± 0.04
	Medium silt, 10–5	5.6	2.5 ± 0.1	12.0 ± 0.02	30.5 ± 0.1	13.7 ± 0.05
	Fine silt, 1–5	11.0	3.9 ± 0.06	10.2 ± 0.2	22.1 ± 0.1	20.1 ± 0.1
	Clay, <1	9.6	4.6 ± 0.31	8.6 ± 0.03	18.2 ± 0.1	24.8 ± 0.1

* LF, light-weight fraction.

tions. Thus, the maximum MRT (63 years) was in the organic matter bound with the clay fraction containing a low amount of plant detritus, whereas the minimum MRT (4.3 years) was in the coarse sand fraction containing a significant admixture of plant detritus.

Changes in the content of young C_4 carbon in dependence on the fraction size were not monotonous in the chernozem. The maximum content (up to 20%) was found in light fractions (Table 5). Concentrations of C_4 carbon and the total organic carbon were 5–10 times lower in the mineral particles than in the light fractions of similar sizes (Table 5). However, mineral fractions contained up to 4% of the young C_4 carbon, which could be due to the incomplete separation of the light fraction by the method of flotation in water. For a more complete extraction, heavy liquid with density 1.4–1.6 g/cm^2 should be used in further studies [3, 7, 17].

The portion of young carbon in the light fractions from the chernozem was significantly lower that that in the light fraction isolated together with the sand fraction from the gray forest soil; the MRT of carbon in the light fractions from the chernozem was significantly higher than that in the light fraction isolated together with the sand fraction from the gray forest soil (Tables 4, 5). According to published data, the MRT of light fractions separated together with coarse mineral particles may vary from 1 to 53 years [17]. The MRT of carbon from the coarse fraction in the gray forest soil varied depending on the weight of plant residues, but it fitted well this range. In the chernozem, the minimum MRT of light fractions reached 185 years in the upper horizon and was close to 800 years in the lower horizons. Thus, the chernozemic soil is characterized by the long MRT of not only humus as a whole but also its labile components, such as the light fraction isolated together with the coarse mineral fraction.

The minimum rate of carbon renewal in the gray forest soil was found in the clay fraction, though the difference between clay and fine silt fractions was small (Table 4). Contrary to the gray forest soil, medium and fine silt fractions in the chernozem had the lowest rates of carbon renewal; the rate of carbon renewal in the clay fraction was significantly higher than that in the silt fraction (Table 5). As a rule, the organic component of silt fractions is most resistant to degradation [3, 14, 17], as it contains stable aromatic compounds and humin. On the contrary, the clay fraction is characterized by the moderate residence time of carbon because of the predominance of aliphatic fragments and polysaccharides of microbial origin in the chemical structure of organic matter. Consequently, the chernozemic soil displays a typical relationship between the rates of organic matter renewal in the silt and clay fractions.

A low rate of carbon renewal in the clay fraction of gray forest soil could be due to the insufficient duration of the experiment: the C_4 carbon had no time to be dispersed uniformly by separate particle-size fractions during five years of the destruction of corm residues. At the same time, in some cases, the low rate of carbon renewal in the clay fraction was observed in long-term (30–40 years) experiments with corn [10, 19]. A small portion of the clay fraction in the gray forest soil (Table 4) in comparison with the chernozem (Table 5) could also be the probable cause of the slow renewal of carbon

Table 5. Carbon distribution by the particle-size fractions of chernozem, variant N120P60K60 (mean ± standard deviation)

Depth	Fraction, μm	Mass, %	C_{org}, %	C/N	$C–C_4/C_{org}$, %	MRT, years
0–20	Coarse sand, 250–1000	12.2 ± 2.1	0.5 ± 0.05	13.5 ± 0.5	0.7 ± 0.1	5779 ± 821
	LF, 250–1000	0.1 ± 0.01	6.2 ± 0.5	17.5 ± 0.2	19.4 ± 1.1	186 ± 10
	Fine sand, 100–250	11.0 ± 0.9	1.1 ± 0.1	12.4 ± 1.1	1.4 ± 0.3	2802 ± 600
	LF, 100–250	2.0 ± 0.5	4.9 ± 0.5	13.7 ± 0.5	15.5 ± 0.5	238 ± 8
	Coarse silt, 10–100	32.2 ± 3.3	1.1 ± 0.1	17.0 ± 0.5	6.9 ± 0.8	557 ± 61
	Medium silt, 5–10	5.6 ± 2.1	5.5 ± 0.3	15.4 ± 0.2	2.2 ± 0.5	1790 ± 407
	Fine silt, 1–5	15.8 ± 1.2	6.6 ± 0.1	13.6 ± 0.3	2.3 ± 0.2	1752 ± 152
	Clay, <1	21.6 ± 1.7	5.0 ± 0.3	10.4 ± 0.2	6.1 ± 0.7	636 ± 73
20–40	Coarse sand, 250–1000	10.4 ± 1.4	0.1 ± 0.02	6.7 ± 1.1	0.03 ± 0.01	135930 ± 44857
	LF, 250–1000	0.1 ± 0.1	5.5 ± 0.3	23.2 ± 0.5	15.3 ± 0.9	246 ± 13
	Fine sand, 100–250	8.1 ± 2.1	0.3 ± 0.01	10.6 ± 0.8	4.1 ± 0.7	956 ± 54
	LF, 100–250	0.1 ± 0.05	3.5 ± 0.4	13.8 ± 0.5	8.7 ± 0.9	440 ± 46
	Coarse silt, 10–100	31.0 ± 1.8	0.6 ± 0.1	16.0 ± 0.5	3.6 ± 0.4	1089 ± 121
	Medium silt, 5–10	1.8 ± 0.5	4.2 ± 0.3	17.1 ± 0.4	0.32 ± 0.3	12602 ± 1265
	Fine silt, 1–5	17.0 ± 1.5	7.0 ± 0.2	15.1 ± 0.2	0.5 ± 0.1	8037 ± 1607
	Clay, <1	26.0 ± 2.1	5.5 ± 0.2	11.7 ± 0.2	1.9 ± 0.2	2276 ± 240
40–60	Coarse sand, 250–1000	12.8 ± 1.3	0.1 ± 0.02	8.7 ± 0.9	1.1 ± 0.1	3671 ± 334
	LF, 250–1000	0.4 ± 0.1	3.0 ± 0.1	13.9 ± 0.5	4.9 ± 0.5	790 ± 81
	Fine sand, 100–250	7.2 ± 3.1	0.2 ± 0.03	9.2 ± 0.8	4.1 ± 0.3	952 ± 70
	LF, 100–250	1.0 ± 0.4	2.6 ± 0.2	12.4 ± 0.3	2.8 ± 0.2	1394 ± 68
	Coarse silt, 10–100	31.1 ± 3.3	0.4 ± 0.05	15.6 ± 0.2	0.4 ± 0.1	10093 ± 2523
	Medium silt, 5–10	3.0 ± 0.4	3.1 ± 0.3	16.5 ± 0.1	0.3 ± 0.05	12115 ± 2019
	Fine silt, 1–5	13.2 ± 1.4	6.0 ± 0.2	15.1 ± 0.2	0.5 ± 0.07	8125 ± 1138
	Clay, <1	25.2 ± 1.5	4.3 ± 0.3	11.2 ± 0.1	0.6 ± 0.1	6286 ± 1048

connected with clay, because of the low capacity of clay particles in the gray forest to sorb labile components of organic matter of C_4 origin.

The concentrations of total and labeled carbon in most of the fractions decreased down the soil profile (Table 5), so that the MRT of carbon in separate fractions from the deep soil horizons increased. The fine silt and clay fractions were an exception, as the maximum concentration of organic carbon in these fractions was determined in the layer of 20–40 cm.

A comparative analysis of carbon distribution in the gray forest soil (with due account for the carbon content in separate fractions and the mass of the fractions) suggests that young carbon is primarily concentrated in the coarse particle-size fractions (Fig. 1). The light fraction in sand and coarse silt particles is enriched in young carbon in comparison with the total carbon: the C_4 carbon in these fractions comprised 8–12 and 33–38% of the total content of C_4 carbon in all the fractions, whereas the total organic carbon retained in these fractions comprised 3–5 and 20–21% of total content of C_{org}, respectively (Fig. 1). The portions of young (C_4-derived) and total organic carbon in the medium silt fraction were approximately similar, and the fractions of fine silt and clay were impoverished in the young carbon. The portions of C_4 carbon in these fractions (26–33 and 10–14%, respectively) were smaller than the portions of total organic carbon retained in them (38–41 and 15–22% of the total content of organic carbon in the soil, respectively). The character of carbon distribution by the fractions varied insignificantly depending on the amount of plant residues entering the soil.

A lower contribution of carbon from the fraction of coarse silt and the high portion (30% in the upper and up to 50% in the lower horizons) of organic carbon bound with the clay fraction (Fig. 2) are characteristic features of the fractional distribution of carbon in the chernozem. The coarse fractions (sand, light fraction, and coarse silt) in the chernozem, as well as in the gray forest soil, were relatively rich in the young C_4 carbon; the fractions of medium and fine silt were impoverished in the young carbon; and the clay fraction contained a second maximum of the young carbon. Similar regularities of the fractional distribution of the young (C_4) car-

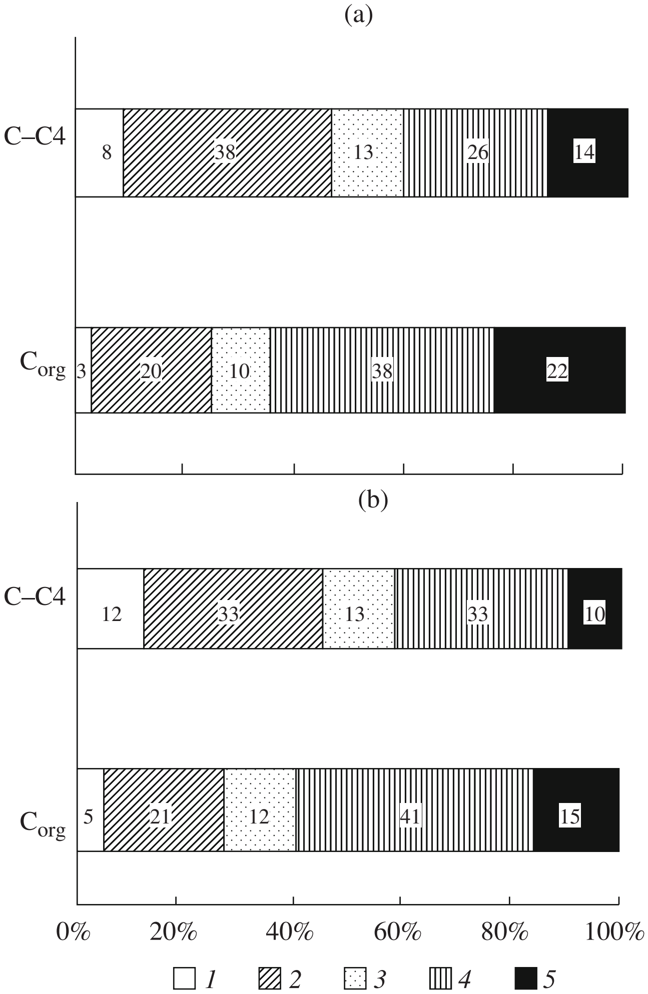

Fig. 1. Distribution of the total organic carbon and the carbon of C_4 origin by the particle-size fractions of gray forest soil upon application of (a) 1.9 and (b) 5.8 kg C/m^2 of plant residues of corn during five years of the experiment. Fractions: (*1*) sand + light fraction, (*2*) coarse silt, (*3*) medium silt, (*4*) fine silt, and (*5*) clay.

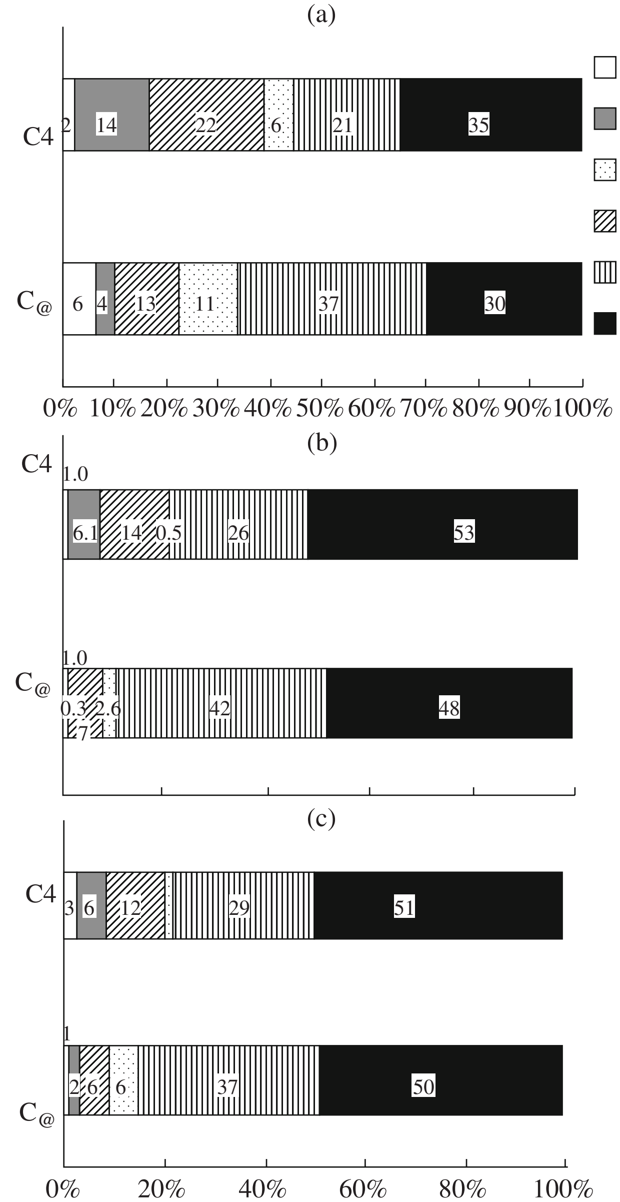

Fig. 2. Distribution of the total organic carbon and the carbon of C_4 origin by the particle-size fractions of leached chernozem under a 40-year-long monoculture of corn at the depths of (a) 0–20, (b) 20–40, and (c) 40–60 cm under 40-year-old monoculture of corn. Fractions: (*1*) sand + light fraction, (*2*) coarse silt, (*3*) medium silt, (*4*) fine silt, and (*5*) clay.

bon derived from corn residues and the total organic carbon were noted for the lower horizons of the chernozem (Fig. 2).

An enrichment of coarse fractions with the young carbon attests to the fact that fragmentation of plant residues plays an important role in the course of their destruction. Plant residues break up into smaller fragments, which come into the soil particle-size fractions. This fragmentation of plant residues proceeds to the size of clay fraction, because up to 4% of carbon in the clay particles was identified as the light fraction with the C/N ratio 22–28 [11] typical of plant residues. The fragmentation of large tree residues on the surface of forest soils and of bog vegetation during the formation of peat soils has been thoroughly studied [6]. The importance of this process in humus formation in mineral horizons is not so obvious, and it can only be studied with the use of fractionation and the analysis of the isotopic composition of carbon. It is probable that the fragmentation of plant residues to the finest size requires long time, because coarse particles are the fraction with the maximum enrichment in young carbon even after 40 years of corn cultivation (Table 5, Fig. 2).

The decomposition of polymeric compounds, migration of the products of decomposition in dissolved form, and sorption of these products on the surface of soil particles play an important part in carbon distribution by particle-size fractions together with the mechanical destruction of plant residues into smaller fragments. The sorption of the products of decomposition from the soil solution occurs mostly in the fine fractions with a large specific surface. Hence, the products of decomposition of plant residues are accumulated mostly in the clay fraction, and this is confirmed by a considerable enrichment of clay particles in the chernozem with young C_4 carbon. The fact that the synthesis of humic substances (the stabilization of carbon in specific thermodynamically stable compounds) occurs predominately on the surface of clay minerals, which are concentrated in the clay particle-size fraction, is also a factor that contributes to the high content of C_4 carbon in the clay fraction in comparison with other fine particles [21].

Data on the isotopic composition of carbon in separate fractions confirm their heterogeneity and allow us to estimate the degree of contamination of the light fractions (that are traditionally considered as labile fractions) with stable C_3 carbon; vice versa, we may judge from these data the degree of participation of the young labile C_4 carbon in the fine fractions with a predominance of stable carbon compounds. Even in the case of the high input of corn residues into the gray forest soil (which exceeded significantly the input of corn-derived carbon in the agroecosystem), only 69% of organic matter in the coarse fraction was composed of the young C_4 carbon (Table 4), whereas a more stable C_3 carbon represented the remaining 31%.

The portion of stable organic matter in the light fractions of the chernozem was even higher (Table 5) and depended on the size of light fractions and the depth of soil horizons. The contribution of C_4 carbon decreased with a decrease in the fraction size: its portion was several percent higher in the fraction >250 μm than in the fraction <250 μm, which was in agreement with a conclusion about the lower rate of renewal of light fractions occluded in microaggregates in comparison with that in the macroaggregates obtained earlier in numerous studies of the aggregate composition of soils [13, 16, 20].

Changes in the land use and fertilization system affect light fractions [7, 8, 15, 20], so it was suggested to consider these fractions together with the microbial biomass as the most labile pool of soil organic matter [15, 17]. Our data suggest that the portion of old carbon in light fractions is relatively large and often exceeds the content of young C_4 carbon. It is likely that the presence of humin particles and metal–humin compounds [3] in light fractions favors stabilization of these fractions in the studied soils.

The content of old C_3 carbon in the stable fine silt and clay fractions exceeded significantly the content of young (C_4) carbon of corn. For example, the portion of C_4 carbon in the form of labile admixtures in the stable clay fraction did not exceed 18% in the gray forest soil and 6% in the chernozem (Tables 4, 5). Consequently, only the combination of particle-size–densitometric analysis and the method of natural ^{13}C abundance make it possible to separate the soil organic matter into labile and stable pools of carbon that are more homogeneous in comparison with the traditional division into light-weight and heavy-weight fractions.

CONCLUSIONS

Evaluation of the rates of renewal of soil organic carbon with the method of natural ^{13}C abundance in the case of substitution of C_4 for C_3 plants has demonstrated that the organic matter in the leached chernozem has a higher resistance to degradation in comparison with the organic matter in the gray forest soil: the MRT of soil carbon in the chernozem varies from 1271 to 1498 years; in the gray forest soil, it depends on the amount of corn residues introduced into the soil and varies from 19 to 63 years. The rate of carbon renewal in the chernozem decreases down the soil profile from 697 years in the upper horizon to 2742 years in a layer of 40–60 cm.

Among the isolated particle-size–densitometric fractions, the maximum rate of carbon renewal is observed in light fractions; the minimum rate, in organomineral compounds of the fine silt fraction. As a rule, the MRT of organic carbon increases with a decrease in the size of separate fractions, except for the clay fraction in the chernozem, in which the renewal rate of organic carbon is almost three times higher than that in the fine silt fraction. The organic matter of particle-size–densitometric fractions is heterogeneous: the portion of the old C_3 carbon is significant in the organic matter of labile light fractions; vice versa, stable organomineral complexes of fine fractions contain an admixture of young C_4 carbon. Among labile organic fractions, the highest portion of the old C_3 carbon is in light fractions of the chernozem. The portion of the young C_4 carbon in light fractions from the upper horizon of the chernozem is only 15–22%. The maximum contribution (18%) of labile admixtures to stable fine fractions is observed in the gray forest soil.

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REFERENCES

1. E. V. Arinushkina, *Manual on the Chemical Analysis of Soils* (Mosk. Gos. Univ., Moscow, 1970) [in Russian].
2. A. F. Vadyunina and Z. A. Korchagina, *Methods for Studying Physical Properties of Soils and Sediments* (Vysshaya Shkola, Moscow, 1973) [in Russian].
3. A. Ya. Vanyushina and L. S. Travnikova, “Organic–Mineral Interactions in Soils: A Review,” Pochvovedenie, No. 4, 418–428 (2003) [Eur. Soil Sci. **36** (4), 379–387 (2003)].

4. E. G. Morgun, T. Boutton, V. M. Telesnina, and M. A. Timofeev, "Accumulation of Organic Matter and Its Dynamics in Soils of Arid Ecosystems," in *Ecology of Biosystems (Problems of Study, Indication, and Prediction): Proceedings of the International Scientific and Practical Conference, Astrakhan', Russia, 2007* (Astrakhan', 2007), Part 1, pp. 213–214.

5. L. I. Petrova, L. A. Ivannikova, A. F. Stulin, and S. Sotakova, "Formation of Plant Biomass," in *Production Dynamics of Plant Biomass and Soil Humus* (Nauka, Moscow, 1992), pp. 11–42 [in Russian].

6. V. N. Kudeyarov, G. A. Zavarzin, S. A. Blagodatskii, et al., *Carbon Pools and Fluxes in Terrestrial Ecosystems of Russia* (Nauka, Moscow, 2007) [in Russian].

7. N. A. Titova and M. Sh. Shaimukhametov, "Organic Matter of Densitometric Fractions from Long-Term Fertilized Chernozems, Dark Gray Forest Soils, and Soddy-Podzolic Soils," in *Role of Organic Matter in the Formation of Soils and Their Fertility: Proceedings of the Dokuchaev Soil Science Institute* (Moscow, 1990), pp. 140–149 [in Russian].

8. W. T. Baisden, R. Amundson, A. C. Cook, and D. L. Brenner, "Turnover and Storage of C and N in Five Density Fractions from California Annual Grassland Surface Soils," Glob. Biogeochem. Cycles **16**, 117–132 (2002).

9. Balesdent J., Mariotti A. Measurement of soil organic matter turnover using ^{13}C natural abundance. In: Mass Spectrometry of Soils. Eds. T. W. Boutton and S. Yamasaki. Marcel Dekker, New York, 1996. 83–111.

10. J. Balesdent, E. Besnard, D. Arrouays, and C. Chenu, "The Dynamics of Carbon in Particle-Size Fractions of Soil in a Forest–Cultivation Sequence," Plant Soil **201**, 49–57 (1998).

11. C. Chenu and A. F. Plante, "Clay-Sized Organo-Mineral Complexes in a Cultivation Chronosequence: Revisiting the Concept of the Primary Organo-Mineral Complex," Eur. J. Soil Sci. **57**, 596–607 (2006).

12. H. P. Collins, R. L. Blevins, L. G. Bundy, et al., "Soil Carbon Dynamics in Corn-Based Agroecosystems: Results from Carbon-13 Natural Abundance," Soil Sci. Soc. Am. J. **63**, 584–591 (1999).

13. Golchin A., Baldock J.A., Oades J.M. A model linking organic matter decomposition chemistry andaggregate dynamics. In: Lal R. (Ed) Soil processes and the carbon cycle. CRC Press, Boca Raton. 1997. p. 245–266.

14. J. Hassink, "Decomposition Rate Constants of Size and Density Fractions of Soil Organic Matter," Soil Sci. Soc. Am. J. **59**, 1631–1635 (1995).

15. H. H. Janzen, C. A. Campbell, S. A. Brandt, et al., "Light-Fraction Organic Matter in Soils from Long-Term Crop Rotations," Soil Sci. Soc. Am. J. **56**, 1799–1806 (1992).

16. J. D. Liao, T. W. Boutton, and J. D. Jastrow, "Organic Matter Turnover in Soil Physical Fractions Following Woody Plant Invasion of Grassland: Evidence from Natural ^{13}C and ^{15}N," Soil Biol. Biochem. **38**, 3197–3210 (2006).

17. M. Lutzow, I. Kogel-Knabner, K. Ekschmitt, et al., "SOM Fractionation Methods: Relevance to Functional Pools and to Stabilization Mechanisms," Soil Biol. Biochem. **39**, 2183–2207 (2007).

18. T. Morita, J. Robinson, J. Alcamo, et al., "Greenhouse Gas Emissions Mitigation Scenarios and Implications," in *Climate Change 2001: Mitigation, Third Assessment Report* (IPCC, Cambridge Univ. Press, 2001), pp. 115–166, http://www.ipcc.ch.

19. P. Puget, R. Lal, C. Izzaurradle, et al., "Stock and Distribution of Total and Corn-Derived Soil Organic Carbon in Aggregate and Primary Particle Fractions for Different Land Use and Soil Management Practices," Soil Sci. **170**, 256–279 (2005).

20. J. Six, R. T. Conant, E. A. Paul, and K. Paustian, "Stabilization Mechanisms of Soil Organic Matter: Implications for C-Saturation in Soils," Plant and Soil **241**, 155–176 (2002).

21. A. G. Zavarzina, "A Mineral Support of Biotic Catalyst Are Essential in the Formation of Highly Polymeric Soil Humic Substances," Eur. Soil Sci. **39** (Suppl. 1), 848–853 (2006).