EKOLOGIJA. 2008. Vol. 54. No. 4. P. 232–238
DOI: 10.2478/v10055-008-0034-9

Carbon pool and sequestration in former arable Chernozems depending on restoration period

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Abandonment of cultivated lands leads to vegetation succession, restoring of soils, and is accompanied by changes in organic carbon pools and microbial community. This study was aimed to quantify the different carbon organic pools (total, labile, recalcitrant, and microbial) in former croplands depending on the period of abandonment (restoration). Our investigations were carried out in 2007 on arable soil under winter wheat and on soils abandoned for 5, 11, 21 and 77 years after land use change from crops to permanent grassland (Haplic Chernozems, Rostov region, Russia, 47°27'N, 39°35'E). Soil organic carbon (SOC) and microbial carbon (C_{mic}) increased proportionately to the duration of soil restoration. The average C_{mic} / SOC ratio was 1.3. The total CO_2–C release during 10 weeks of incubation was the highest in arable soil and soil after 5 years of restoration. The abandonment of cultivated soils resulted in an increase of recalcitrant SOC pool: 20.6 mg C g^{-1} in arable soil vs. 28.6 mg C/g in 77-yr grassland. The mean residence time of recalcitrant C in soils after 11–77 years of restoration was 1.9–2.2 times longer than that in arable soil. Labile C decreased from 0.25 mg C g^{-1} in arable soil to 0.12 mg C g^{-1} in soil after 77 years of restoration. Therefore, carbon accumulation in soils after land use change from arable to permanent grassland was mainly caused by sequestration of the recalcitrant C pool.

Key words: land use change, abandonment, set-aside, Chernozems, carbon accumulation, microbial biomass, labile, recalcitrant and total pools of organic carbon, mean residence time of C

INTRODUCTION

The stock of organic carbon is governed by the balance between C input through plant residues and C losses, mainly through decomposition (Орлов, 1996; Paustian et al., 2000). The carbon stock may increase or decrease depending on numerous factors including climate, vegetation type, nutrient availability, disturbance, land use, and management practices (Six, Jastrow, 2002). In natural ecosystems, the total soil organic pool is rather stable (Six et al., 2002). However, any changes in land use affect the quality and quantity of soil organic carbon (SOC), and a new equilibrium (saturation) level is reached in some decades (Powlton, 1995; Орлов и др., 1996; Reeder et al., 1998; West, Post, 2002). Six et al. (2002) suggested that the existence of C saturation level is based on physicochemical processes that stabilize or protect organic compounds in soil.

The most important processes that lead to an increase of the organic carbon pool in soil are: (1) the input of organic residues, (2) the enrichment of deeper soil layers by organic matter (OM) by increasing the belowground phytomass and active perturbation of soil by soil fauna, and (3) the formation of the organic–mineral complex protecting OM (Орлов и др..., 1996; Paustian, 2000; Post, Kwon, 2000; Shevtsova et al., 2003). When agricultural lands are no longer used for cultivation and are allowed to revert to natural vegetation or replanted with perennial vegetation, soil organic carbon can accumulate (Reeder et al., 1998; Dugas et al., 1999; Lal, 1999; Frank, Dugas, 2001; Guo, Gifford, 2002; Poulton et al., 2003). Land use change from arable to permanent grassland results in the OM enrichment of soil profile and increase of carbon residence time in soil.

Post and Kwon (2000) reviewed the literature that reports changes in soil organic carbon after land use changes that favour C accumulation. They observed a large variation in the length of time for and the rate of C accumulation in soil related to the productivity of recovering vegetation, physical and biological conditions in the soil, the past history of soil organic carbon inputs, and physical disturbance. Average C accumulation rates were similar for forest and grassland establishments: 33.8 and 33.2 g C m^{-2} y^{-1}, respectively (Post, Kwon, 2000). Guo and Gifford (2000) have suggested that soil C stocks increase after land use change from native forest to pasture (+8%), crop to pasture or plantation (+19%), and crop to secondary forest (+53%). Larionova et al. (2003) found that grazing resulted in a higher soil C accumulation than afforestation, and the mean rates of C-sequestration after establishment of perennials were 63–182 g C m^{-2} y^{-1}

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and 22–43 g C m^{-2} y^{-1} (layer 0–60 cm) for Luvisols and Albeluvisols, respectively.

For the functioning of a soil ecosystem, the turnover of SOC is more important than the total content of SOC (Six, Jastrow, 2002). Carbon turnover is most often quantified as carbon mean residence time (MRT) or the half-life ($T_{1/2}$) of C in the soil. The MRT of carbon in a pool is defined as the average period of C in the respective pool at steady state. The total SOC consists of various pools that differ in availability to decomposers (Орлов и др., 1996; Paul et al., 1997; Six et al., 2002). The CENTURY model of soil organic matter (Parton et al., 1987) divides soil C into active, slow, and passive pools, with MRTs of 1.5, 25, and about 1000 yrs, respectively. For a given set of biotic and abiotic conditions, the turnover of different SOC pools depends on the quality and biochemical recalcitrance of OM, its accessibility to decomposers, soil texture, particle size, and clay mineralogy (Sorensen, 1974; Dadal, Bridge, 1996; Six et al., 1999, 2002).

Chernozems are typical soils of steppes and prairies and play an important role in the global carbon cycle since they have the highest C stock among mineral soils (Mikhailova, Post, 2006). Due to the active agricultural use of Chernozems and especially their intensive tillage, a significant depletion of C stocks in these soils took place during the last 100–200 years (Хмелев, 1989). About 29% of the initial carbon stock has been lost by Chernozems in the West-Siberian region from 1930 to 1990 (Титлянова, Наумов, 1995; Титлянова и др., 1998). For Chernozems of West Russia (Kursk and Penza regions), C losses amounted to 19.5 ± 12% of the initial C stock (Артемьева, 2008). Despite the many studies done to estimate the decrease of C stocks in Chernozems, studies that show what periods are necessary for the restoration of SOC after the abandonment and grassland establishment as well as what amounts of C can be sequestered in Chernozems during a few decades after restoration are scarce (Belleli, Marhezini, 2007).

Therefore, this study was aimed to (1) estimate changes in carbon stock and carbon accumulation rate in restoring Chernozems, (2) quantify the different carbon organic pools (total, labile, recalcitrant, and microbial) in the former arable Chernozems depending on the stage of restoration, and (3) assess the mean residence time for labile and recalcitrant C pools.

MATERIALS AND METHODS

Soils

Soil samples (layer 20 cm) were taken in September 2007 from arable land under winter wheat and lands abandoned in 1932, 1986, 1996, and 2002 (Rostov region, Russia, 47°27'N, 39°35'E). Soil was classified as Haplic Chernozem containing micellar carbonates. The sites were closely located, and the variability in the main soil properties (texture, mineralogy, pH, etc.) was negligible. After land use change from crops to permanent grassland, the process of soil restoration took place. The sites presented the following self-restoring chronosequence: arable (or 0-moment), 5, 11, 21, and 77 years after conversion. The pH values (water : soil = 1 : 2.5) varied between 6.95 and 7.18, and the bulk density of soil changed from 1.04 g cm^{-3} in arable to 1.16–1.24 g cm^{-3} in restoring soils.

Analyses of C content, C stock, and C accumulation rate

The total soil organic carbon (SOC) was determined by the dichromate oxidation procedure and colometric analyses of solution after heating at 140–160 °C for 20 min (Орлов, Гришина, 1981). Bulk density data (BD, g cm^{-3}) were used to convert SOC (g per 100 g soil) to C stock (S_C, g m^{-2}) in the 0–20 cm layer according to the following formula:

$$S_C = SOC \cdot BD \cdot 20 \cdot 10^2. \tag{1}$$

The carbon accumulation rate (R_{CA}, g C/m^{2}yr) was estimated using the following equation:

$$R_{CA} = (RS_C - AS_C) / D, \tag{2}$$

where RS_C and AS_C are stocks of carbon in restoring and arable soils, respectively (g m^{-2}), and D is the period of soil restoring (yr).

Determination of carbon immobilized in microbial biomass. We used the fumigation-extraction method (Vance et al., 1987) to estimate the carbon stored in microbial biomass (C_{mic}). Carbon concentration in 0.05 M K_2SO_4 extracts before and after fumigation was determined with a CN analyzer (Elementar, Germany). The amount of C_{mic} (µg C g^{-1} of soil) was calculated according to the following formula (Joergensen, 1996):

$$C_{mic} = \Delta C / k_{EC}, \tag{3}$$

where ΔC is the difference between C contents in 0.05 M K_2SO_4 extracts after and before the fumigation procedure (µg C g^{-1}), and $k_{EC} = 0.45$ is the exactable part of microbial biomass.

Determination of labile and recalcitrant (stabile) pool of carbon

The root-free soil samples (2 mm sieved) were adjusted to 40% of their water holding capacity (WHC) and incubated at 20 °C for one week using a special micromulti-container. Then soil samples (weight 1.5 g) were wetted with distilled water to a moisture corresponding to 60% of WHC and incubated at the same temperature over the next 10 weeks. During the experiment, we controlled the water content to equal 60% of WHC. The CO_2 released during the incubation was adsorbed by 1 M NaOH. The content of CO_2-C was measured by titration excess in special CO_2 traps with standardized 0.01 M HCl. The CO_2 amount was measured daily during the first four days, every 2–3 days over the next 10 days and every week through 3–10 weeks of incubation.

The first-order two-component exponential model (Katterer et al., 1998) was used for the analysis of cumulative CO_2–C evolution (C_{cum}, mg Cg^{-1} of soil):

$$\begin{aligned} C_{cum} = \alpha \cdot C_o \cdot (1 - e^{(-k1 \cdot T)}) + (1 - \alpha) \cdot C_o \cdot \\ \cdot (1 - e(-k2 \cdot T)), \qquad 0 \le \alpha \le 1, \end{aligned} \tag{4}$$

where C_o is the initial content of total C in the soil (µg C g^{-1}), $\alpha \cdot C_o$ and $(1 - \alpha) \cdot C_o$ are the initial content of C in the labile and recalcitrant pools, respectively (µg C g^{-1}), k1 and k2 are the corresponding mineralization rate constants for each C pools, and T is the time (days).

Data analyses and statistics

The results presented are arithmetic means of three replicates and standard error (SE). A non-linear least-squares regression analysis (Eq. 4), provided by STATISTICA 6.0, was used to calculate the parameters from cumulative C mineralization data. The model fits were evaluated by the correlation coefficient (R).

RESULTS AND DISCUSSION

Effect of soil restoration on total carbon content and stock

The establishment of perennial vegetation after land use change from arable to grassland resulted in a significant C accumulation in soils. The SOC content (0–20 cm layer) increased from 2.08 ± 0.03 to 2.24 ± 0.04% for the first 5 years of restoration of Chernozems and reached 2.87 ± 0.07% in the 77-yr grassland (Table 1). The C stock increased proportionately with the restoration period and changed from 4330 g $\mathrm{C\,m^{-2}}$ in arable Chernozems to 6650 g $\mathrm{C\,m^{-2}}$ after 77 years of restoration. The average C accumulation rate was maximal (280 g $\mathrm{C\,m^{-2}\,y^{-1}}$) during the first 5 years of restoration, and then soils sequestered C at a rate of 41 and 5 g $\mathrm{C\,m^{-2}\,y^{-1}}$ for the following 16 and 56 yrs, respectively. The average R_{CA} for the entire 77-yr period of restoration amounted to 30 g $\mathrm{C\,m^{-2}\,y^{-1}}$.

Post and Kwon (2000) also observed the highest rate of C accumulation during the early stage of perennial vegetation growth. Silver et al. (2000) estimated the reforestation of abandoned tropical agricultural land and pasture sequester C in the soil to proceed at a rate of 130 g $\mathrm{C\,m^{-2}\,y^{-1}}$ for the first 20 yrs and then at an average rate of 41 g $\mathrm{C\,m^{-2}\,y^{-1}}$ for the following 80 yrs. Also, the change from conventional tillage (CT) to no-till (NT) can sequester 57 ± 14 g $\mathrm{C\,m^{-2}\,y^{-1}}$ (West, Post, 2002). The carbon sequestration rates, with a change from CT to NT, can be expected to peak in 5 to 10 yrs with SOC reaching a new equilibrium in 15–20 yrs.

Due to changes in the land use system in Russia in the last 15–20 years, significant areas of cultivated lands ($4.37 \cdot 10^3$ km^2) were abandoned in the Rostov region during 1990–2004 (Сельское хозяйство…, 2004). On an average, the share of Chernozems was 70% of the total of abandoned lands ($3.06 \cdot 10^3$ km^2). According to our calculation, the average rate of carbon accumulation for the first 5–20 years of abandonment was 164 g $\mathrm{C\,m^{-2}\,y^{-1}}$. Based on these rates, Chernozems in the Rostov region sequestered about 9 Tg C after 1990 due to the land use changes.

Effect of soil restoration on microbial carbon content

Microbial carbon is the most sensitive pool which reflects various alterations in an ecosystem. It is well known that the ratio of C_{mic} and SOC is a very important ecological parameter characterizing the status of microbial community and the maturity of an ecosystem (Insam, Domsch, 1988). The C_{mic} / SOC ratio was found to increase from 0.25% in young ecosystems to 7% in mature ones and was stable in the climax community (Anderson, 1994). The C_{mic} / SOC ratio depends on climatic conditions and land use changes. The C_{mic} / SOC ratio was significantly lower in the monoculture as compared to crop rotation and in arable soils in comparison with soils under native vegetation (Insam, 1990).

Our results showed that the content of microbial carbon (0–20 cm layer) increased proportionally to the period of restoration and changed from 251–263 µg C $\mathrm{g^{-1}}$ in the arable and the 5-yr grassland to 445 µg C/g soil after 77 years of grassland establishment (Table 1). The share of C_{mic} in SOC was the lowest (1.17–1.21%) in the arable soil and in the 5-yr grassland, and reached 1.55% after 77 years of restoration. Although the increase of the C_{mic} / SOC ratio was not significant, the obtained results are comparable with the conclusions of Anderson (1994) that higher values of the C_{mic} / SOC ratio are found in a succession from arable to native steppe.

CO_2–C evolution rate and cumulative release of carbon during incubation

On the first day of incubation (right after wetting the soil from 40 to 60% of WHC), the CO_2 evolution rate from soil varied from 51 to 85 µg C $\mathrm{g^{-1}\,h^{-1}}$ depending on the stage of their restoration (Fig. 1). After 7 days of incubation, the rate of CO_2 evolution decreased rapidly and ranged within 20.4–21.7 µg C $\mathrm{g^{-1}\,h^{-1}}$. After 14 days, the intensity of CO_2 release flattened for all soils studied and did not exceed 13–16 µg C $\mathrm{g^{-1}\,h^{-1}}$ through the following 56 days of incubation (steady-state phase). A short burst of CO_2 release during the first day of incubation was caused by soil rewetting. Many authors suggested that C mineralization was increased immediately after soil rewetting (Van Gestel et al., 1993; Bottner et al., 1998; Halverson et al., 2000; Miller et al., 2005). The high CO_2 evolution rates during the first 7–10 days indicated a rapid depletion of the readily mineralizable fraction. After 14 days when the CO_2 evolution rate reached the constant level in all soils, the most labile fraction was exhausted, and the resistant and stable fraction of soil organic matter was being mineralized (Ellert, Bettany, 1988; Wander et al., 1994).

Table 1. **Total and microbial carbon pools, average rate of carbon accumulation and CO_2–C release during incubation of Chernozems after different periods of restoring (layer 0–20 cm)**

Parameter	Arable land	Restoration period			
		5 yr	11 yrs	21 yrs	77 yrs
SOC, %	2.08 ± 0.03	2.24 ± 0.04	2.33 ± 0.03	2.66 ± 0.04	2.87 ± 0.07
C stock, g $\mathrm{C\,m^{-2}}$ (0–20 cm)	4330	5720	5620	6380	6650
Carbon accumulation rate, (R_{CA}), g $\mathrm{C\,m^{-2}\,y^{-1}}$	–	279	117	97	30
C_{mic}, µg C $\mathrm{g^{-1}}$ soil	251 ± 0.1	263 ± 1.5	301 ± 6.6	335 ± 11.4	445 ± 6.8
C_{mic} / SOC, %	1.21	1.17	1.29	1.26	1.55
Total CO_2–C losses during 70 days (C_{cum}), g C $\mathrm{g^{-1}}$ soil	1.19 ± 0.02	1.01 ± 0.08	0.69 ± 0.02	0.77 ± 0.03	0.76 ± 0.01
C_{cum} / SOC, %	5.72	4.51	2.95	2.90	2.64

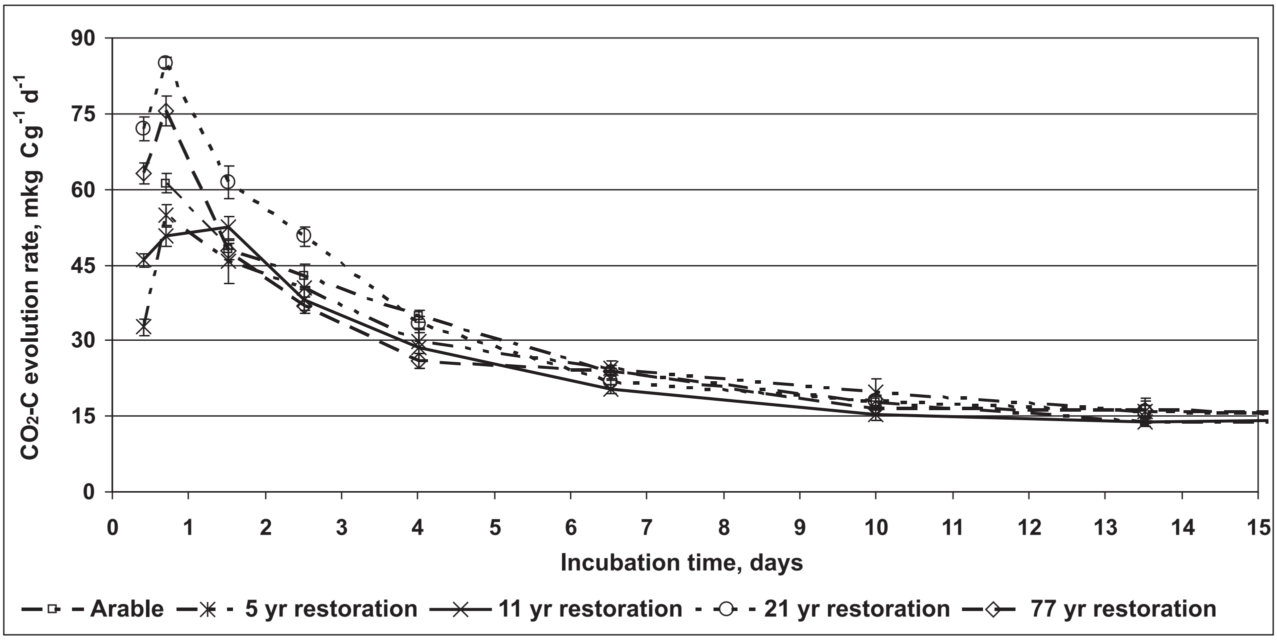

Fig. 1. CO_2 evolution rate of Chernozems in increasing restoration periods (the first 15 days of incubation)

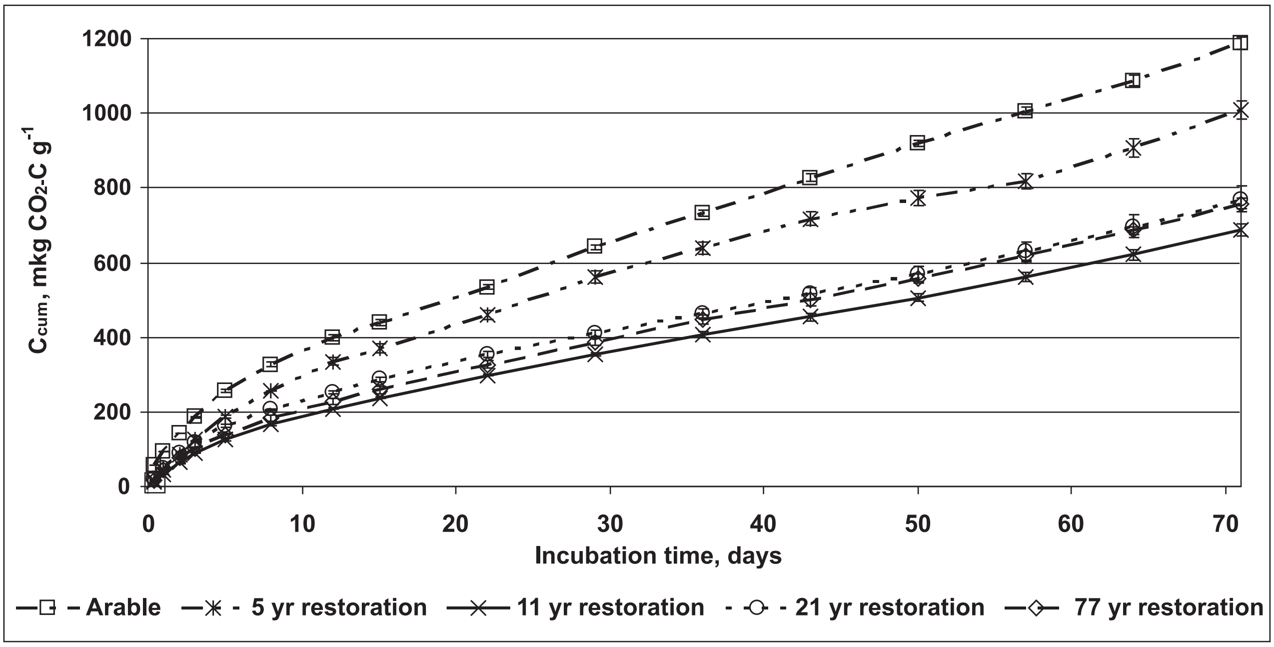

Fig. 2. Cumulative CO_2–C release from soils during 70 days of incubation

The cumulative CO_2–C release (C_{cum}) due to the mineralization of organic matter was highest in arable soil and reached 1.19 μg C g^{-1} in 10 weeks of incubation (or 5.7% of SOC). In restoring Chernozems, the total CO_2–C release was about 1.5–2 times lower than in arable soil and varied from 0.69 to 0.77 μg C g^{-1} (or 2.6–2.9% of SOC). In our study, the change in land use from arable to permanent grassland resulted in a decrease in the C_{cum} / SOC ratio proportionally to the duration of soil restoration. Sarminento and Bottner (2002) suggested that 1.3–1.5% of SOC was mineralized in the cultivated soil and 15-yr fallow during 12 weeks of incubation. About 3–12% of SOC was released as CO_2 from various Australian soils during 96 days of incubation (Mendham et al., 2002).

The higher rates of C mineralization in arable soil and soil after 5 years of restoration as compared with soils after 11–77 years of restoration indicated that C accumulated during the initial restoration was sequestered mainly in available pools. During the further restoration, these available pools will be transformed to more stable pools with slower MRT and decomposition rates.

The labile and recalcitrant pools of SOC and its turnover

The cumulative CO_2–C release from soils studied during 10 weeks of incubation is illustrated in Fig. 2. Despite the lowest C

Table 2. **Content and mean residence time (MRT) of labile and recalcitrant carbon pools in Chernozems of different stages of restoring**

Site	SOC content		MRT	
	C labile, mg C/g soil	C recalcitrant, mg C/g soil	C labile, days	C recalcitrant, years
Arable	0.24	20.6	3.0	4.1
5 yrs of restoration	0.25	22.9	6.8	5.9
11 yrs of restoration	0.12	22.6	4.0	7.8
21 yrs of restoration	0.16	26.4	3.6	8.5
77 yrs of restoration	0.13	28.6	3.5	8.9

content, the maximal CO_2 evolution was measured from the arable soil and soil after 5 years of restoration. The first-order two-component model (Eq. 4) fitted the cumulative SOC mineralization data sufficiently well for all soils ($R > 0.99$, $P = 0.95$). This model describes the decomposition of two separate pools with a different rate of degradation in the total SOC: the labile pool (C_{lab}) with a high degradation rate (k1) and the recalcitrant C pool (C_{rec}) with a low decomposition rate (k2). These coefficients (k1 and k2) were used to estimate the MRT of C_{lab} and C_{rec}, respectively (Table 2). Similar models were widely applied to predict C mineralization of soil organic matter or plant materials (Bottner et al., 1998; Katterer et al., 1998; Wang et al., 2004).

Титлянова и др. (1999) have suggested that the higher respiratory activity during the first week of incubation is a result of an active decomposition of the labile fraction of SOC. After decomposition of readily available carbon, the respiratory activity of soils decreased and stabilized at a lower level typical of resistant SOC pools. Sarmiento and Bottner (2002) also found an active decomposition of readily available organic matter and a decrease of the labile pool of carbon during the first days of incubation.

According to the CO_2 efflux dynamics, the content of C_{lab} was highest (0.25 mg C g^{-1}) in the arable soil and soil after 5 years of restoration, and it decreased gradually to 0.12–0.16 mg C g^{-1} in 11–77-year grasslands (Table 2). These results show that the initial abandonment of soils causes C sequestration mainly in available pools. The further restoration leads to a higher stabilization of these readily available pools. The share of the labile pool in SOC also declined from 1.14% in arable soil to 0.45% in soil after 77 years of restoration. The slowly decomposable fraction (recalcitrant, C_{rec}) was the major pool in the total SOC and varied from 98.9% in arable soil to 99.6% in the 77-yr grassland. We observed a clear tendency of increase of the recalcitrant fraction in the total organic carbon pool during the restoration of the formerly cultivated Chernozems: from 20.6 mg Cg^{-1} of soil in the arable soil to 28.6 mg Cg^{-1} of soil in the 77-yr grassland. The mean residence time of labile C changed from 3 to 7 days and did not depend on the restoration period. The MRT of recalcitrant C in soils after 11–77 years of abandonment was 1.9–2.2 times higher than that in arable soil (8–9 years versus 4 years).

It is important to note that the MRT of labile and recalcitrant pools of carbon were calculated for laboratory conditions which are favorable for mineralization: 20 °C and 60% of WHC). In fact, these conditions are very rare in the Rostov region which belongs to the dry steppe bio-climatic zone. Therefore, the real MRT will be longer than that presented in this study. Nevertheless, this investigation allows us to conclude that carbon accumulation in soils after land use change from arable to permanent grassland was mainly caused by the sequestration of recalcitrant C pools.

CONCLUSIONS

1. The land use change from cultivation to permanent grassland leads to restoration of arable Chernozems and a significant increase of SOC content in the former plough layer. The average rate of carbon accumulation was 117–279 g C m^{-2} y^{-1} during the first 5–11 years of soil restoration and amounted to 30 g C m^{-2} y^{-1} for the 77-yr period.

2. The abandoned Chernozems in the Rostov region sequestered about 9 Tg C during 1990–2004 due to land use changes.

3. The content of microbial carbon in the topsoil of Chernozems increased proportionally from 251 µg C g^{-1} in the arable soil to 445 µg C g^{-1} in the 77-yr grasslands. The share of C_{mic} in SOC was the lowest (1.17–1.21%) in the arable soil and the 5-yr grassland and reached 1.55 after 77 years of restoration.

4. The cumulative CO_2–C release due to the mineralization of organic matter was highest in arable soil: 1.19 mg C g^{-1} soil for 10 weeks of incubation (or 5.7% of SOC). In restoring Chernozems, the total CO_2–C release was about 1.5–2 times lower (0.69–0.77 mg C g^{-1} or 2.6–2.9% of SOC).

5. A tendency of a decrease of the labile fraction in the total organic carbon pool was observed during the restoration of the former cultivated Chernozems: from 1.14% in arable soil to 0.45% in the 77-yr grassland. The MRT of labile C changed from 3 to 7 days and did not depend on the restoration stage.

6. Recalcitrant carbon was the major pool in the total SOC (98.9–99.6%). The restoration of soils resulted in an increase of the recalcitrant fraction in the SOC pool: 20.6 mg C g^{-1} in arable soil vs. 28.6 mg C g^{-1} in the 77-yr grassland. The MRT of the C_{rec} pool in SOC after 11–77 years of restoration was 1.9–2.2 times higher than that in arable soil. Therefore, carbon accumulation in soils after land use change from cultivation to permanent grassland was mainly caused by the sequestration of the recalcitrant C pool.

ACKNOWLEDGEMENT

This study was supported by DAAD, RFBR (project N 07-04-01333), and Program of RAS Presidium N16. Authors are grateful to Director of Agroboistation, Dr. V. Ponomarenko (Southern Federal University, Rostov-na-Donu) for the opportunity to sample soils for investigations, Dr. E. Blagodatskaya (Institute of Physicochemical and Biological Problems in Soil Science, RAS) for her assistance in planning the incubation experiment and useful discussions, and Dr. Bidisha Majumder for correcting our English.

Received 28 May 2008
Accepted 15 October 2008

References

1. Anderson T. H. 1994. *Physiological analysis of microbial communities in soil: Applications and Limitations. Beyond the Biomass*. London. P. 67–76.
2. Belleli Marchezini L. 2007. *Analyses of the carbon cycle of steppe and old field ecosystems of Central Asia*. PhD thesis. 227 p. (available http://www.unitus.it)
3. Bottner P., Austrui F., Cortez J., Billes G., Couteaux M. M. 1998. Decomposition of ^{14}C- and ^{15}N-labelled plant material, under controlled conditions, in coniferous forest soils from a north-south climatic sequence in Western Europe. *Soil Biol. Biochem.* Vol. 30. P. 597–610.
4. Dadal R. S., Bridge B. J. 1996. Aggregation and organic matter storage in sub-humid and semi-arid soils. In: Carter M. R., Stewart B. A. (eds.). *Structure and Organic Matter Storage in Agricultural Soil*. CRC Press: Boca Raton, FL. P. 263–307.
5. Dugas W. A., Heuer M. L., Mayeux H. S. 1999. Carbon dioxide fluxes over bermuda grass, native prairie, and sorgum. *Agricultural and Forest Meteorology.* Vol. 93. P. 121–139.
6. Ellert B. H., Bettany J. R. 1988. Comparison of kinetic models for describing net sulfur and nitrogen mineralization. *Soil Sci. Soc. Am. J.* Vol. 52. P. 1692–1702.
7. Frank A. B., Dugas W. A. 2001. Carbon dioxide fluxes over a northern, semiarid, mixed-grass prairie. *Agricultural and Forest Meteorology.* Vol. 108. P. 317–326.
8. Guo L. B., Gifford R. M. 2002. Soil carbon stock and land use change: a meta analysis. *Global Change Biology.* Vol. 8. P. 345–360.
9. Halverson L. J., Jones T. M., Firestone M. K. 2000. Release of intracellular solutes by four soil bacteria exposed to dilution stress. *Soil Sci. Soc. Am. J.* Vol. 64. P. 1630–1637.
10. Insam H., Domsch K. H. 1988. Relationship between soil organic carbon and microbial biomass on chronosequences of reclamation sites. *Microbial Ecology.* Vol. 15. P. 177–188.
11. Insam H. 1990. Are the soil microbial biomass and basal respiration governed by the climatic regime? *Soil Biol. Biochem.* Vol. 22. P. 525–532.
12. Jorgensen R. G. 1996. The fumigation-extraction method to estimate soil microbial biomass: Calibration of the k_{EC} value. *Soil Biol. Biochem.* Vol. 28. P. 25–31.
13. Kätterer T., Reichstein M., Andren O., Lomander A. 1998. Temperature dependence of organic matter decomposition: a critical review using literature data analyzed with different models. *Biol. Fertil. Soils.* Vol. 27. P. 258–262.
14. Lal R., Follett R. F., Kimble J., Cole C. V. 1999. Managing US cropland to sequester carbon in soil. *J. Soil Water Concerv*. Vol. 54. P. 374–381.
15. Larionova A. A., Rozonova L. N., Yevdokimov I. V., Yermolayev A. M., Kurganova I. N., Blagodatsky S. A. 2003. Land-use change and management effects on carbon sequestration in soils of Russia's South Taiga zone. *Tellus B.* Vol. 55. P. 331–337.
16. Mendham D. S., O'Connell A. M., Grove T. S. 2002. Organic matter characteristics under native forest, long-term pasture, and recent conversion to eucalyptus plantations in Western Australia: microbial biomass, soil respiration, and permanganate oxidation. *Aust. J. Soil Res.* Vol. 40. P. 859–872.
17. Mikhailova E. A., Post C. J. 2006. Organic carbon stocks in the Russian Chernozems. *Eur. Soil Sci*. Vol. 57. P. 330–336.
18. Miller A. E., Schimel J. P., Meixner T., Sickman J. O., Melack J. M. 2005. Episodic rewetting enhances carbon and nitrogen release from chaparral soils. *Soil Biol. Biochem.* Vol. 37. P. 2195–2204.
19. Parton W. J., Schimel D. S., Cole C. V., Ojima D. S. 1984. Analysis of factors controlling soil organic matter levels in Great Plains Grasslands. *Soil Science Soc. Am. J.* 1987. Vol. 51. P. 1173–1179.
20. Paul E. A. 1997. Dynamics of organic matter in soils. *Plant and Soil.* Vol. 76. P. 275–285.
21. Paustian K., Collins H. P., Paul E. A. 1977. Management control on soil carbon. In: *Soil Organic Matter in Temperate Ecosystems: Long-term Experiments in North America*. CRC Press. P. 15–49.
22. Paustian K., Six J., Elliott E. T., H. W. 2000. Management options for reducing CO$_2$ emissions from agricultural soils. *Biogeochemistry.* Vol. 48. P. 147–163.
23. Post W. M., Kwon K. C. 2000. Soil carbon sequestration and land use change: processes and potential. *Global Change Biol.* Vol. 6. P. 317–327.
24. Poulton P. R., Pye E., Hargreaves P. R., Jenkinson D. S. 2003. Accumulation of carbon and nitrogen by old arable land reverting to woodland. *Global Change Biology.* Vol. 9. P. 942–955.
25. Poalton P. R. 1995. The importance of long-term trials in understanding sustainable farming systems: the Rothamsted experience. *Austr. J. Exper. Agric.* Vol. 35. P. 825–834.
26. Powlson D. S., Jenkinson D. S. 1976. The effects of biocidal treatments on metabolism in soil. Gamma irradiation, autoclaving, air-drying and fumigation. *Soil Biol. Biochem.* Vol. 8. P. 179–188.
27. Reeder J. D., Schuman G. E., Bowman R. A. 1998. Soil C and N changes on conservation reserve program lands in the Central Great Plains. *Soil Tillage Res.* Vol. 47. P. 339–349.
28. Sarmiento L., Bottner P. 2002. Carbon and nitrogen dynamics in two soils with different fallow times in the high tropical Andes: indications for fertility restoration. *Appl. Soil Ecol.* Vol. 19. P. 79–89.
29. Shevtsova L., Romanenkov V., Sirotenko O., Smith P., Smith Jo U., Leech P., Kanzyvaa S., Rodionova V. 2003. Effect of natural and agricultural factors on long-term soil organic matter dynamics in arable soddy-podzolic soils – modelling and observation. *Geoderma.* Vol. 116. P. 165–189.
30. Silver W. L., Osterlag R., Lugo A. E. 2000. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. *Restor. Ecol.*. Vol. 8. P. 394–407.
31. Six J., Elliott E. T., Paustian K. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Sci. Soc. Am. J.* Vol. 63. P. 1350–1358.

32. Six J., Conant R. T., Paul E. A., Paustian K. 2002. Stabilization mechanisms of soil organic matter: implication for C-saturation of soils. *Plant and Soil*. Vol. 241. P. 155–176.
33. Six J., Jastrow J. D. 2002. Organic matter turnover. In: *Encyclopedia of Soil Science*. Marcel Dekker. P. 936–942.
34. Sorensen L. 1974. The influence of clay on the rate of decay of amino acid metabolites synthesized in soil during decomposition of cellulose. *Soil Biol. Biochem*. Vol. 7. P. 171–177.
35. Van Gestel M., Merckx R., Vlassak K. 1993. Microbial biomass response to soil drying and rewetting. The fate of fast- and slow-growing microorganisms in soils from different climates. *Soil Biol. Biochem*. Vol. 25. P. 109–123.
36. Vance E. D., Brookes P. C., Jenkinson D. S. 1987. An extraction method for measuring soil microbial biomass C. *Soil Biol. Biochem*. Vol. 19. P. 703–707.
37. Wander M. M., Traina S. J., Stinner B. R., Peters S. E. 1994. Organic and conventional management effects on biologically active soil organic matter pools. *Soil Sci. Soc. Am. J.* Vol. 58. P. 1130–1139.
38. Wang W. J., Baldock J. A., Dalal R. C., Moody P. W. 2004. Decomposition dynamics of plant materials in relation to nitrogen availability and biochemistry determined by NMR and wet-chemical analysis. *Soil Biol. Biochem*. Vol. 36. P. 2045–2058.
39. West T. O., Post W. M. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci. Soc. Am. J.* Vol. 66. P. 1930–1946.
40. Артемьева З. С. 2008. *Органические и органо-глинистые комплексы агрогенно-деградированных почв*. Автореф. дисс. ... доктора биол. наук. Москва. 48 с.
41. Орлов Д. С., Бирюкова О. Н., Суханова Н. И. 1996. *Органическое вещество почв России*. Москва: Наука. 254 с.
42. Орлов Д. С., Гришина Л. А. 1981. *Практикум по химии гумуса*. Москва: МГУ. 213 с.
43. *Сельское хозяйство, охота и лесоводство в России, 2004 год*. Статистический сборник. 2004. Москва: Росстат. 478 с.
44. Титлянова А. А., Наумов А. В. 1995. Потери углерода из почв Западной Сибири при их сельскохозяйственном использовании. *Почвоведение*. № 11. С. 1357–1362.
45. Титлянова А. А., Булавко Г. И., Кудряшова С. Я., Наумов А. В., Смирнов В. В., Танасиенко А. А. 1998. Запасы и потери органического углерода в почвах Сибири. *Почвоведение*. № 1. С. 51–59.
46. Титлянова А. А., Кудряшова С. Я., Якутин М. В., Булавко Г. И., Миронычева-Токарева Н. П. 1999. Запасы лабильного углерода в экосистемах Западной Сибири. *Почвоведение*. № 3. С. 332–341.
47. Хмелев В. А. 1989. *Лессовидные черноземы Западной Сибири*. Новосибирск: Наука. 201 с.

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ANGLIES ATSARGŲ IR KAUPIMOSI BUVUSIUOSE ARIAMUOSE JUODŽEMIUOSE PRIKLAUSOMYBĖ NUO DIRVONAVIMO LAIKO

Santrauka

Ariamų žemių dirvonavimas sąlygoja augalijos tęstinumą ir dirvožemio atkūrimą per anglies atsargų bei mikroorganizmų bendrijų kaitą. Šio tyrimo tikslas buvo nustatyti dirvožemio anglies atsargų (bendrųjų, judriųjų, stabiliųjų ir mikrobinės kilmės) buvusiose ariamose žemėse priklausomybę nuo dirvono amžiaus. Mūsų tyrimai daryti 2007 m. ėminiuose iš 0–20 cm ariamojo dirvos sluoksnio žieminių kviečių pasėlyje ir iš 5, 11, 21 ir 77 m. ilgalaikių žalienų (tipingieji juodžemiai, Rusijos Rostovo sritis, 47°27'N, 39°35'E). Tyrinėta dirvožemio organinė anglis (DOC, dichromato oksidacijos metodu), mikrobinės kilmės anglis (C_{mic}, fumigacijos–ekstrakcijos metodu), judrioji ir stabilioji anglis (inkubacijos periodas 10 savaičių esant 20°C temperatūrai ir 60% drėgmės imlumui). Nustatyta, kad dirvožemio organinės anglies (DOC) ir mikrobinės kilmės anglies (C_{mic}) kiekiai didėjo proporcingai dirvonavimo laikotarpiui. Vidutinis C_{mic} / DOC santykis buvo 1,3%. Daugiausia CO_2-C per 10 savaičių inkubacinį periodą išsiskyrė iš ariamos dirvos ir iš dirvos po 5 metų atkuriamojo laikotarpio. Dėl dirbamų žemių dirvonavimo didėjo stabiliosios anglies atsargos: 20,6 mg C g^{-1} – ariamoje dirvoje, 28,6 mg C g^{-1} – 77-ių metų žalienoje. Vidutinis stabiliosios C gyvavimo laikas dirvoje po 11–77 dirvonavimo metų buvo 1,9–2,2 karto ilgesnis, kaip ariamoje dirvoje. Judriosios C kiekis sumažėjo nuo 0,25 mg C g^{-1} ariamoje dirvoje iki 0,12 mg C g^{-1} dirvoje po 77-ių dirvonavimo metų. Todėl ariamas dirvas pakeitus ilgalaikėmis žalienomis daugiausia anglies kaupėsi dėl stabiliosios C atsargų kaupimosi (sekvestravimo).

Raktažodžiai: juodžemiai, anglies kaupimasis, mikrobų biomasė, judriosios, stabiliosios ir bendrosios organinės anglies atsargos, vidutinis anglies gyvavimo laikas