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Changes in carbon stocks of former croplands in Russia

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Changes in land use affect significantly the amount of organic carbon stored in the soil and vegetation. Since 1990, the land use system in Russia has been considerably changing and more than 10 Mha of croplands were abandoned. The carbon balance of cultivated soil under fallow was compared with that of soils abandoned 4, 8, 13, and 28 years ago and converted naturally to permanent grassland (Moscow region, Russia, 54°50'N 37°37'E). The carbon balance in the abandoned ecosystems varied from –116 to –392 g C/m^2 · yr depending on the period of abandonment. The average net ecosystem productivity of abandoned lands in Russia was –236 g C/m^2 · yr. Since the 90s, the total C-sink for the Russian territory may be estimated to 231–802 Tg C per year due to the conversion of former croplands to permanent grasslands. Based on own field studies and literature analysis, the carbon accumulation rates (R_{CA}) for the main soil types have been estimated. The mean values of R_{CA} were 132 ± 21 and 70 ± 8 g C/m^2 · yr for the periods 0–15 and 15–30 years of abandonment, respectively. Due to the land use change from croplands to permanent grasslands, the total C accumulation in Russian soils amounted to 184–673 Tg C during 1990–2004 and can reach 282–1030 Tg C by 2020.

Key words: land use change, net ecosystem production, CO_2 emission, carbon balance, soil organic carbon, C accumulation rate, abandoned lands

INTRODUCTION

Land use change can cause a change in land cover and associated changes in the amount of organic carbon stored in soil and vegetation (Bolin, Sukumar, 2000). Since the early 1990s, a significant area of agricultural lands in Russian Federation has been abandoned due to the economic crisis (Larionova et al., 2003a). Abandonment of cultivated lands leads to vegetation succession accompanied by changes in carbon fluxes among the atmosphere, plant, and soils. After abandonment, soils may act as an important carbon sink according to the new ratio between carbon inflows and outflows (Guo, Gifford, 2002). Recent studies have shown that the former croplands after 5–10 years of abandonment act as a stable sink of CO_2 from atmosphere and their C balance constitute –114–(–778) g C/m^2 · yr (Vuichard et al., 2006; Belleli Marchesini, Valentini, 2007; Kurganova et al., 2007).

Besides, when cultivated lands are abandoned they usually accumulate carbon and nitrogen, both in the vegetation and in the soil (Paustian et al., 2000; Poulton et al., 2003). The amount of organic carbon stored in the soil results from the net balance between the rate of soil organic carbon inputs and the rate of mineralization of carbon pools. Due to the changing of land use from agriculture to grassland or forest, the average rates of carbon accumulation were estimated to be 33.2 and 33.8 g C/m^2 · yr, respectively (Post, Kwon et al., 2000). Changes in management alter the quality of organic matter in the soil, and the magnitude of these alterations may be caused by the duration of abandonment. Thus, Silver et al. (2000) estimated that reforestation of abandoned tropical agricultural land and pasture sequesters C in the soil at a rate of 130 g C/m^2 · yr for the first 20 yr and then at an average rate 41 g C/m^2 · yr for the following 80 yrs. It was found that the change from conventional tillage (CT) to no-till (NT) can sequester 57 ± 14 g C/m^2 · yr (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. The objects of this study were: (1) to quantify the alterations of carbon fluxes in abandoned lands after different periods of land use change, and (2) to estimate carbon accumulation in Russian soils during 1990–2020.

MATERIALS AND METHODS

Sites and soils

This study was carried out in 2007 on the former arable lands of the Experimental Field Station of the Institute of Physicochemical and Biological Problems in Soil Science of the Russian Academy of Sciences (Moscow region, Russia, 54°50'N 37°37'E). Carbon balance in cultivated soil under fallow was compared with that of soils abandoned 4, 8, 13 (2 plots), and 28 years ago and converted naturally to permanent grassland. At present, some plots (grasslands 13 and 28 yrs old) are cut, others (4, 8 and 13 yrs old) are uncut. The soil in the study plots was classified as a grey forest soil (loamy Phaeozems) subject to erosion of different intensity. The detailed botanical description and general soil characteristics of the plots are given by Kurganova et al. (2007).

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Determination of net primary productivity

The aboveground phytomass of the abandoned lands was estimated within seasonal dynamics (from June to August) according to cuts made 1–2 times per month from 0.25 m^2 plots in four replicates. The plants were cut near the soil surface, sorted into main botanical groups (cereals, forbs, legumes and mosses), and these groups were sorted into fractions of living phytomass (biomass) and dead plants (current falloff). The soil monoliths (diameter 10 cm and height 20 cm) were taken in the same plots after cutting the plants. In laboratory, the monoliths were washed to separate roots (living and dead). The sorted samples of the plants, litter, and roots were dried to their absolutely dry weight. The annual aboveground net production (ANP) and belowground net production (BNP) were calculated using the budget equations (Methods of Studying..., 1978). The net primary productivity (NPP) represented the sum of ANP and BNP and characterized the input of carbon from the atmosphere. The share of carbon in the dry mass of roots and plants was taken to be equal to 40% (Methods of Studying..., 1978).

Measurement of total and microbial soil respiration

The total loss of carbon from ecosystems represented the summary annual soil emission of CO_2 (total soil respiration, TSR). It was determined for the soils under the fallow and 28-yr grassland on the basis of the year-round weekly field measurements using the close chamber method. The CO_2 emission rate from soils of other cenoses was determined during the summer season, and then the summary annual soil respiration was estimated on the basis of our previous long-term CO_2 emission measurements and models developed (Kurganova et al., 2004). The extended description of this technique and principles of calculation were given in our earlier works (Kurganova et al., 2003, 2004).

The microbial respiration (MR) of soil was calculated taking into account the contribution of roots respiration (RR) to the total soil respiration. The contribution of roots (C_{RR}) to the TSR was determined in various cenoses all the year round using the method of substrate-induced respiration (Larionova et al., 2003a). Then, the MR was calculated according to the following formula:

$$MR = TSR(1 - C_{RR}), \qquad (1)$$

where MR is the annual microbial respiration (g $C/m^2 \cdot yr$), TSR is the total soil respiration (g $C/m^2 \cdot yr$), and C_{RR} is the share of respiration of roots in the total CO_2 emission from the soil.

Net ecosystem production

The budget of C–CO_2 in the ecosystems (net ecosystem production (NEP), g $C/m^2 \cdot yr$) was estimated as a difference between the respiration of microorganisms decomposing the organic matter and litter (MR) and the net primary production (NPP):

$$NEP = MR - NPP. \qquad (2)$$

The negative NEP values indicate a carbon sink in the ecosystem. The positive values of NEP suggest the domination of carbon inflows over carbon outflows, and therefore the ecosystems act as a source of carbon.

Estimation of carbon accumulation rate in soils

We gathered all available information about the changing C content in soils after land use change from agriculture to permanent grassland (Kurganova, Lopes de Gerenyu, 2007). The analysis of data base has shown that the literature knowledge is rather fragmentary and concerns the limited set of soil types and the period of abandonment. To amend the existing information, our own investigations were carried out on main soil types*: Albeluvisols (sod-podzolic soil, Vladimir region), Phaeozems (grey forest soil, Moscow region), Chernozems (chernozem, Rostov region), and Kastanozems (chestnut soil, Volgograd region). The carbon content in arable soil (zero-moment) was compared with that in soils abandoned 12 years ago (Albeluvisols), 2, 6, 11, 26 years ago (Phaeozems), 10, 20, 76 years ago (Chernozems), and 15 years ago (Kashtanozems). The soil samples were taken in each soil profile to the depth of 50–60 cm (each 10 cm, 3 replicates); C content was determined by the dichromate oxidation method. The soil C organic (SOC) pool was calculated taking into account the bulk density of each horizon. To allow the comparison of all selected sites, we focused on the SOC-pool of the first 20 cm, because it is mostly changed after conversion of arable land to grassland. The carbon accumulation rate (R_{CA}, g $C/m^2 \cdot yr$) was calculated according to the following formula:

$$R_{CA} = (RS_C - AS_C) / D, \qquad (3)$$

where RS_C and AS_C are the SOC pool in the 0–20 cm layer of abandoned (restoring) and arable soils (g C/m^2), respectively; D is the period of abandonment, years.

Data analyses and statistics

The results presented are arithmetic means and standard errors (SE). The correlation analysis between R_{CA} and D was carried out using the logarithmic function.

RESULTS AND DISCUSSION

Carbon balance of abandoned lands

A botanical survey clearly showed that the vegetation of abandoned agricultural lands changed to permanent grasslands after 5–8 years of abandonment. Aboveground productivity (AGP) varied from 41 g $C/m^2 \cdot yr$ in cultivated land under fallow to 363 g $C/m^2 \cdot yr$ in a 13-yr cut grassland (Table 1). Belowground productivity changed from 46 g $C/m^2 \cdot yr$ in a fallow plot to 400 g $C/m^2 \cdot yr$ in 8-year grassland where cereals prevailed. The net primary production increased from 97 g $C/m^2 \cdot yr$ in the fallow to 757 g $C/m^2 \cdot yr$ in the 13-yr uncut grassland. The ratio between BGP and AGP for abandoned lands was typical for grassland vegetation and comprised 1.1–3.1 depending on their botanical composition.

A large difference in summer CO_2 fluxes from soils of abandoned ecosystems was observed (Table 1). The total summer respiration increased with the age of abandonment: from 48 g C/m^2 in a fallow plot to 192 g C/m^2 in a 28-yr grassland. A close

* We cite soil names according to Soil Classification of the FAO and corresponding name of soils (in brackets) according to the Russian Soil Classification (Stolbovoi, 2000).

Table 1. **Productivity, carbon losses and balance (g C/m^2 · yr) in abandoned soils of different age**

Parameter	Fallow	Abandoned lands				
		4 year uncut	8 years uncut	13 years cut	13 years uncut	28 years cut
Productivity:						
NPP, including:	97	577	530	757	568	539
aboveground (ANP)	41	274	130	363	268	201
belowground (BNP)	46	303	400	393	300	338
CO_2–C fluxes from soils:						
Total (TSR), including	175	408	463	505	542	586
summer season*	48	134	152	166	177	192
beyond the summer season	127	274	311	339	365	394
Microbial (MR), including:	127	294	334	364	390	422
summer season	31	86	97	106	114	123
beyond the summer season	97	209	237	258	277	299
Carbon balance, NEP = MR – NPP	+31	–282	–196	–392	–178	–116

* Summer season means the period from June to August, beyond the summer season means the period between September and May.

positive correlation between summer soil CO_2 fluxes and BGP was found (correlation coefficient, R = 0.90, F = 0.01). This is a good evidence of the significant participation of root systems in the total soil respiration during the summer period. The total annual carbon losses from soils amounted to 175–586 g C/m^2 · yr. The obtained values of summer CO_2 fluxes and TSR were 1.2–2.2 times lower than those in 2004, and the average values based on long-term monitoring CO_2 fluxes from arable and grassland soils of the Moscow region (Kurganova et al., 2004, 2007). It can be explained by a small amount of precipitation during spring and summer seasons: 231 mm in 2007 versus 365 mm on average.

Our previous investigations (Larionova et al., 2003b) showed that the share of roots in the total soil respiration of grasslands averaged to 36% for the summer season (June–August) and 24% beyond the summer (September–May). According to this comment and using formula (3), we found that the microbial respiration varied from 127 g C/m^2 · yr in a fallow plot to 422 g C/m^2 · yr in a 28-yr grassland.

The magnitude of carbon balance in the ecosystems of the abandoned lands (NEP) corresponded to the difference between MR of soils and NPP. It varied from –116 to –392 g C/m^2 · yr depending on the period of abandonment (Table 1). The results presented here indicate that all the ecosystems studied, except the fallow plots, acted as a carbon sink. The carbon balance of one-year grassland (fallow plots) was positive and close to zero. Our data agree with the results of similar research of carbon balance in former arable lands of the steppe region in Russia (Vuichard et al., 2006; Belleli Marchesini, Valentini, 2007). The former field ecosystems in the Khakass Republic acted as a carbon sink, the NEE (Net Ecosystem Exchange) being –210 g C/m^2 · yr at the early stage (5 years of abandonment) and –114 g C/m^2 · yr at a mature stage (steppe).

Our conclusions also agree well with the first results obtained within the framework of the European Green Grass project (Soussanna et al., 2002). These results demonstrated that the investigated grasslands situated in 10 different European countries also acted as a sink of carbon with the NEE varying from –50 to –550 g C/m^2 · yr.

The average values of carbon sink in abandoned lands of Russia have been shown to amount to –236 g C/m^2 · yr. It is well known that since 1990 the land use system in Russia has been considerably changed and significant areas of croplands were abandoned. According to different sources, the area of abandoned lands varies from 9.8 to 34 M ha. Therefore, due to the conversion of former croplands to permanent grasslands, the total C sink for the Russian territory may be estimated as 231–802 Tg C per year. Belleli Marchesini and Valentini (2007) suggest that the magnitude of carbon sequestration in steppes and old field ecosystems in the Russian Federation may amount to 170 Tg C per year. Our investigations allow to conclude that the conversion of low-fertile arable lands into permanent grasslands can be a good alternative to artificial reforestation for the additional sequestration of atmospheric carbon dioxide.

Estimates of changes in the total pool of organic carbon in Russian soils since 1990

Based on our own field studies and literature analysis, we have estimated the carbon accumulation rates for main soil types: Albeluvisols, Phaeozems, Chernozems and Kastanozems. The carbon sequestration rate changed from 28 g C/m^2 · yr to 484 g C/m^2 · yr depending on soil genesis and the period of abandonment. As a rule, the C accumulation rate was higher during the first years after land use change from arable to grasslands. For the first 15 years after abandonment, the mean C accumulation rate in topsoil (0–20 cm) varied from 66 ± 24 g C/m^2 · yr in chestnut soils (Kastanozems) to 145 ± 52 g C/m^2 · yr in Chernozems (Table 2).

Table 2. **Average carbon accumulation rate in 0–20 cm layer (R_{CA} ± SE, g C/m^2 · yr) in main soil types depending on the period of abandonment**

Soil type	Period of abandonment		
	1–15 yrs	1–30 yrs	1–77 yrs
Albeluvisols	131 ± 13	111 ± 22	97 ± 22
Phaeozems	134 ± 36	105 ± 26	102 ± 23
Chernozems	175 ± 52	152 ± 44	109 ± 32
Kastanozems	66 ± 24	–	–
Total	132 ± 21	111 ± 16	99 ± 14

The mean values of R_{CA} were 132 ± 21 and 70 ± 8 g C/m^2 · yr for the first 15 yrs of abandonment and for the next 15 yrs, respectively. The relationship between the rate of carbon accumulation (R_{CA}) and the period of abandonment (D) was satisfactorily described by the negative logarithmic function (Figure, Table 3). The above estimates of carbon accumulation rate in soils of the European part of Russia are higher than the previous mean values (33–34 and 57 ± 14 g C/m^2 · yr) cited in recent reviews by Post and Kwon (2000) and West and Post (2002). This difference may be explained by existence of very young abandoned lands (2–5 years ago) with a high R_{CA} among the sites studied.

The first and very rough estimate of +660 Tg C for the total C accumulation in the Russian territory due to changes in land use after 1990 was done by Larionova et al. (2003a). The area of 34 million ha and period from 1990 to 2002 were used in this calculation. Vuichard et al. (2006) estimated the total C accumulation for the territory of the former USSR using the "Orchidee" model. According to their calculations, the total C accumulation amounted to +116–(+131) Tg C from 1993 to 2000 and +214 Tg C in the next 10 yrs (2000–2010). The popular model RothC was used for assessment of soil C sequestration by Romanovskaya (2006). The results presented in this study indicated the C losses of 5.5 Tg C during the first 13–15 years of soil abandonment (1990 to 2002).

Based on the results of this study, we have calculated that the total C accumulation induced by conversion of croplands to grasslands amounted to 184–673 Tg C for the Russian territory during 1990–2004 and can reach 282–1030 Tg C by 2020. These estimates may be improved by the force of correction of areas of abandoned lands in the Russian Federation. The assessment presented in this study can have a considerable impact on the Kyoto implementation policies.

Table 3. **Logarithmic models for approximation of carbon accumulation rate in 0–20 cm layer in the main soil types depending on the period of abandonment**

Soil type	n	Model	R^2
Albeluvisols	5	–54Ln(D) + 238	0.89*
Phaeozems	10	–60Ln(D) + 261	0.74*
Chernozems	18	–70Ln(D) + 317	0,.71*
Kastanozems	6	–17Ln(D) + 111	0.21^{ns}
Total	41	–53Ln(D) + 250	0.63*

* – model is significant at F < 0.01; ns – model is insignificant

CONCLUSIONS

1. After 4–5 years of abandonment, the former arable soils act as a stable sink of carbon. The value of carbon balance in the ecosystems of the abandoned lands varied from –116 to –392 g C/m^2 · yr depending on the period of abandonment. The average net ecosystem productivity of abandoned lands in Russia was –236 g C/m^2 · yr.

2. Since the 90s, the total C sink for the Russian territory may be estimated at 231–802 Tg C per year due to the land use change from croplands to permanent grasslands. Conversion of low-fertile arable lands to natural ecosystems can be a good alternative to artificial reforestation in order to sequester an additional amount of atmospheric carbon dioxide.

3. Based on our own field studies and literature analysis, the carbon accumulation rates (R_{CA}) for the main soil types have been estimated. For the first 15 years after abandonment, the mean C accumulation rate in the 0–20 cm layer varied from 66 ± 24 g C/m^2 · yr in Kastanozems to 145 ± 52 g C/m^2 · yr in Chernozems. The mean values of R_{CA} were 132 ± 21 and 70 ± 8 g C/m^2 · yr for the periods 0–15 and 15–30 years of abandonment, respectively.

4. Due to the land use change from croplands to permanent grasslands, the total C accumulation in Russian soils

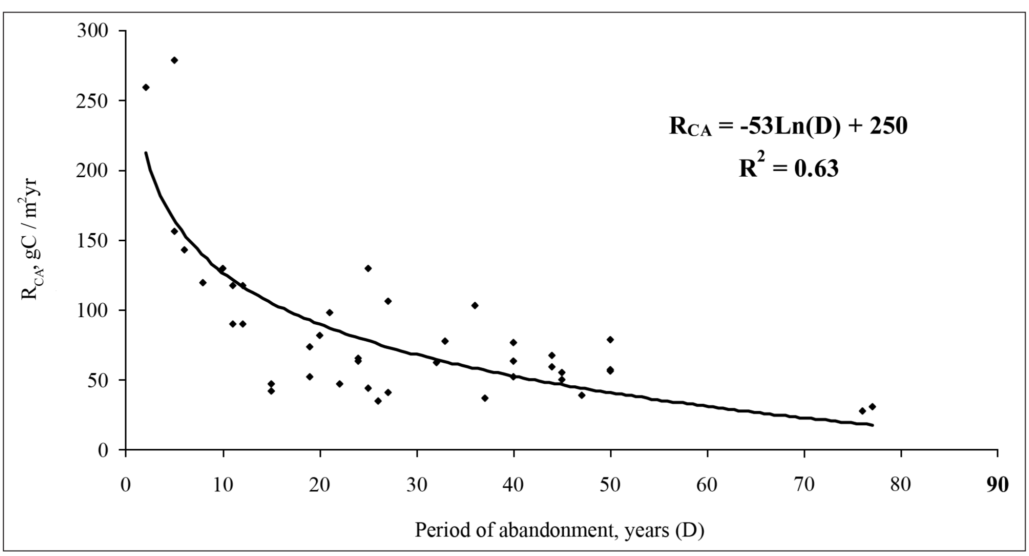

Figure. Relationship between the rate of carbon accumulation (R_{CA}) in the topsoil (0–20 cm) and period of abandonment (D) amounted to 184–673 Tg C during 1990–2004 and can reach 282–1030 Tg C by 2020. These estimates may be improved by the force of correction of areas of abandoned lands in the Russian Federation.

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ANGLIES IŠTEKLIŲ POKYČIAI RUSIJOS DIRVONUOJANČIOSE ŽEMĖSE, PASIKEITUS ŽEMĖNAUDAI

Santrauka
Žemėnaudos kaita turėjo įtakos dirvožemyje ir augaluose sukauptos organinės anglies kiekiui. Nuo 1990 m. Rusijoje keitėsi žemėnauda, ir daugiau kaip 10 mln. ha augalininkystei naudotos žemės tapo pūdymuojančia. Šio darbo tikslas: 1) įvertinti kiekybinius anglies srauto pokyčius pūdymuojančiose žemėse, praėjus skirtingam laikui po žemėnaudos pakeitimo ir 2) įvertinti anglies kaupimąsi Rusijos dirvožemiuose 1990–2020 m.

Anglies balansas (AB) pūdymuojančiose dirvose palygintas su dirvomis, kurios prieš 4, 8, 13 ir 28 m. natūraliai tapo ilgaamžiais žolynais (priemolio juosvažemiai (*Phaeozems*), Maskvos regionas, Rusija, 54°50'N37°37'E). Atskleista, kad buvusios augalininkystei naudojamos dirvos kaupia anglį ir jos balansas −116–(−392) g C/m^2/metus. Remiantis šiais lauko tyrimais daroma išvada, kad per 4 ar 5 žolių augimo metus C kiekis stabiliai didėjo. Vidutiniškai AB dėl nenaudojamų dirvų konversijos į ilgaamžius žolynus buvo 236 C/m^2/metus. Nuo 1990 m. suminis sukauptos anglies kiekis Rusijoje galėjo siekti 231–802 Tg C per metus dėl augalininkystei naudojamų dirvožemių konversijos į žolynus.

Remiantis atliktais tyrimais ir literatūros analize nustatytas anglies kaupimosi lygis šiose pagrindinėse dirvožemių grupėse: balkšvažemiuose (*Albeluvisols*), juosvažemiuose (*Phaeozems*), juodžemiuose (*Chernozems*) ir kaštonžemiuose (*Kastanozems*). Anglies kaupimas (angl. *carbon sequestration*) kito nuo 28 iki 484 g C/m^2/metus ir priklausė nuo dirvožemio genezės ir žemėnaudos pasikeitimo trukmės. Anglies kaupimosi lygis nustojus arti ir žemei apaugus žolynu buvo didžiausias pirmaisiais metais. Pasikeitus žemėnaudai, per pirmuosius 15 metų vidutinis anglies kaupimasis kaštonžemiuose (*Kastanozems*) buvo nuo 66 ± 24 g C/m^2/metus ir juodžemiuose (*Chernozems*) – iki 145 ± 52 g C/m^2/metus. Vidutinė R_{CA} reikšmė buvo atitinkamai 132 ± 21 ir 70 ± 8 g C/m^2/metus 0–15 ir 15–30 metų periodams po žemėnaudos pasikeitimo. Rusijos dirvožemiuose 1990–2004 m. dėl žemėnaudos konversijos iš arimo į žolyną anglies kaupimas buvo 184–673 Tg C, iki 2020 m. jis gali pasiekti 282–1030 Tg C. Šie skaičiavimai gali būti pakoreguoti, patikslinus žemės plotą Rusijoje, kuriame pasikeitė žemėnauda.

Raktažodžiai: žemėnaudos kaita, ekosistemos produkcija, CO_2 emisija, dirvožemio organinė anglis, anglies balansas, dirvonuojanti žemė