

Updated estimate of carbon balance on Russian territory

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(Manuscript received 30 November 2009; in final form 11 June 2010)

ABSTRACT

The land use system in Russia changed considerably after 1990: 30.2 million ha of croplands were abandoned. Based on the own field investigations that were carried out in abandoned lands of different age (Luvic Phaeozems, deciduous forest zone; Moscow region, 54°50'N, 37°37'E), it has been shown that after 4–5 yr of abandonment, the former croplands acted as a stable sink of CO₂. The net ecosystem production (NEP) in the post-agrogenic ecosystems averaged $245 \pm 73 \text{ g C m}^{-2} \text{ yr}^{-1}$ for the first 15 yr after land use change that corresponds to an estimated $74 \pm 22 \text{ Tg C yr}^{-1}$ for the total area of abandoned lands in Russian Federation. Currently, the Russian territory acts as an absolute sink of atmospheric CO₂ at a rate about $0.90 \text{ Pg C yr}^{-1}$. Using three different approaches, it was demonstrated that after 1990, the carbon sequestration in Russian soils (0–20 cm layer) has averaged $34 \pm 2.2 \text{ Tg C yr}^{-1}$. This soil C forms net biome production (NBP) where carbon lifetime is much longer than in 'Kyoto forests'. Thus, the post-agrogenic ecosystems in Russia provide with the additional CO₂ sink in NEP and NBP that could annually compensate about 25% of the current fossil fuel emissions in the Russian Federation.

1. Introduction

Net primary production (NPP) and respiration of soil microorganisms (microbial flux, MF) are the principal fluxes in the global carbon cycle. The C exchange between atmosphere, soils and vegetation is one of the key processes that need to be assessed as a part of Kyoto protocol (Smith, 2004). According to various estimates, the difference between the amounts of C exchanged between terrestrial ecosystems and the atmosphere results in a net terrestrial carbon sink of about $2.1\text{--}2.7 \text{ Pg C yr}^{-1}$ (Ito, 2003; www.globalcarbonproject.org). Understanding the nature of terrestrial carbon sinks requires a full carbon budget applied over a large spatial scale and a long time frame. The measurement of terrestrial carbon fluxes at a regional scale can provide an independent estimate of changes in carbon balance, as well as insight into the processes that effect full global carbon account.

Russia occupies more than 1/9th of global land area therefore its carbon budget is an essential contribution to the global carbon budget. The first rough estimate of carbon balance on Russian territory was based on abundant empirical data on total soil respiration (TSR) and NPP (Kudeyarov and Kurganova,

1998). Soil CO₂ emissions were shown to be very close to the carbon uptake on the Russian territory and that, in general, North Eurasian terrestrial ecosystems function under steady state conditions. However, non-soil emission CO₂ fluxes (disturbances) were not considered in this evaluation. Further estimates of Russian C budget (Kudeyarov, 2000, 2005; Nilsson et al., 2000) were more correct since soil microbial flux was included in C-balance calculation, and non-respiratory processes (such as fossil fuel, industry, agriculture, forest fire and post-fire emissions, insect damage, etc.) was taken into account as well. According to an estimate by Nilsson et al. (2000), the Russian territory acted as a net source of CO₂ in the amount of $0.53 \text{ Pg C yr}^{-1}$ in 1990 and will be continued to be a net source with $0.16\text{--}0.39 \text{ Pg C yr}^{-1}$ in 2010. The uncertainty of these values is estimated by authors to be 129%. It should be noted that these estimated amounts are in conflict with data on CO₂ exchange between the atmosphere and terrestrial ecosystems in different regions and climatic zones obtained by an international team of experts (Gurney et al., 2003). Using 17 different models, authors showed that, according to most applied models, ecosystems of Boreal Asia and Europe act as a stable sink of CO₂. Almost all territory of Russia is located in these regions meaning that the Russian terrestrial ecosystems are sinks of atmospheric CO₂ as well. According to estimates given by Kudeyarov (2000, 2005), the total C sink of Russian territory calculated for early nineties is about $0.8\text{--}1.0 \text{ Pg C yr}^{-1}$. Shvidenko et al. (2009) also concluded that terrestrial

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DOI: 10.1111/j.1600-0889.2010.00467.x

ecosystems of Russia in 2005 served as a net sink of 0.49 Pg C yr⁻¹. High uncertainty and contradiction of Russian C budget calculations was mainly caused by great difference in evaluations of non-soil CO₂ emissions (Kudeyarov, 2005).

Soils contain about 1500 Pg of organic C world wide (Batjes, 1996), which is about three times the amount of C in vegetation and twice the amount in the atmosphere (IPCC, 2000). Total pool of soil organic carbon (SOC) on Russian territory (for the first 100-cm depth of soil, including peat soils) is about 1/5 of world SOC pool (Rojkov et al., 1996; Orlov, 1998). Soil carbon is the critical parameter to consider for long-term carbon storage and it forms the net biome production (NBP) in terrestrial ecosystems (Steffen et al., 1998; Kudeyarov et al., 2007).

Any changes in land use have a significant effect on C balance, its main elements, and storage of SOC (Houghton, 2003). When the agricultural lands are no longer used for cultivation and converted to natural vegetation, the SOC can accumulate (Guo and Gifford, 2002; Poulton et al., 2003). It has been estimated that agricultural soils have a potential to sequester between 0.4 and 0.9 Pg C yr⁻¹ due to improved management of existing agricultural soils, restoration of degraded lands, more extensive use of abandoned lands, and restoration of wetlands (Paustian et al., 1998). Despite the large pool of organic carbon in soils and significant shifts in SOC that often accompany the human activities, changes in soil organic C were not explicitly included in the first version of the Kyoto protocol (Article 3.4). Later, the IPCC Panel on Land Use, Land Cover and Forestry devised guidelines to include the changes in SOC in national carbon accounts (Schlesinger, 2000).

Since the early 1990s, after the collapse of the Soviet collective farming system, a radical decrease in area of agricultural lands in Russian Federation has been observed. According to the official Russian statistic data (Federal State Statistics Service, 2009), 43 million ha of agricultural lands (including 30.2 million ha of arable) were abandoned after 1990 and the ratio between croplands and grasslands was significantly changed. It was the largest land use change (LUC) of the 20th century in the northern Hemisphere (Lyuri et al., 2008) that has governed substantial shifts in C balance and total SOC pool on the territory of Russian Federation.

Russia has ratified the Kyoto Protocol for an assigned target of anthropogenic greenhouse gas (GHG) emissions for the period between 2008 and 2012 that is not to overtop the GHG emission levels of 1990. To accomplish this agreement, the member-countries of Kyoto Protocol can control the fossil fuel emission only or can include CO₂ sinks due to forest and cropland management to their portfolio as well (Smith, 2004).

In this study, we firstly assess the additional ecosystem CO₂-sink induced by abandonment of arable lands of Russian Federation after 1990 based on the own field investigations (Moscow region) and available literature data related to other abandoned croplands in Russia. The results obtained allowed us to update the earlier estimates of carbon balance on Russian territory that

did not include the C-sink due to agriculture abandonment to full carbon account of Russia. The second aim was to assess the shift of SOC-pool in according to the radical LUCs in Russian Federation since 1990. For that, we compiled the available literature data reporting about the organic C build-up in Russian soils after conversion of cropland to natural vegetation and carried out own investigations in different regions of European Russia, where representative soil types exposed to abandonment during different periods. Using three methodological approaches, the total C accumulation due to the LUC in the Russian soils after 1990 has been calculated. Finally, the obtained estimates of the total CO₂ sink to post-agrogenic ecosystems and SOC recovery are compared to the anthropogenic CO₂ emissions on Russian territory.

2. Methods and approaches

2.1. Estimate of carbon balance of abandoned lands

Carbon balance and its main components were estimated in 2004 and 2007 in the post-agrogenic ecosystems (*Luvic Phaeozems* of 1, 4, 5, 8, 10, 13, 25 and 28 yr old) that were converted naturally from arable to permanent grassland (*deciduous forest zone*; Moscow region, Russia, 54°50'N, 37°37'E). NPP of post-agrogenic ecosystems represented the sum of above- and below-ground productions and characterized the CO₂-input from the atmosphere. The aboveground productivity (AGP) was estimated by biometric method (Yermolaev and Shirshova, 2000) from early June to late August (one to two times per month, four replicates). To determine the belowground productivity, the soil monoliths (diameter 10 cm and height 20 cm) were taken in the same plots where AGP was estimated. In laboratory, the soil monoliths were washed to separate roots (living and died). The annual aboveground net production (ANP) and belowground net production (BNP) were calculated using the budget equations (Titlyanova and Tesargova, 1991). The share of carbon in the dry mass of roots and plants was taken to be equal to 40%.

Losses of CO₂ from ecosystems were equivalent to the annual microbial CO₂ fluxes (MF) from soils. They were determined on the basis of the field measurements of TSR using the closed chamber method (Kurganova et al., 2003). The MF from soil studied was calculated taking into account the contributions of roots respiration (RR) to the TSR. The share of RR in TSR was early determined in grassland ecosystems during the year-round using the substrate induced respiration method (Larionova et al., 2003b). It has been found to average 36% for the summer season (June–August) and 24% beyond the summer (September–May). More detailed descriptions of studied soils, vegetation, and methods for NPP, TSR and MF determination were published previously (Kurganova et al., 2003, 2007, 2008).

The budget of C-CO₂ in the post-agrogenic ecosystems (net ecosystem production, NEP) was estimated as the difference between NPP and MF. The positive NEP values indicate a carbon

dioxide sink in the ecosystem, while the negative values of NEP suggest that the ecosystems act as a source of CO₂. Therefore, NEP is the carbon remaining in ecosystem and belongs to the medium-term carbon storage (Steffen et al., 1998).

2.2. Estimation of carbon accumulation rate in soils

All available information about changing C storage in Russian soils after LUC from agriculture to natural vegetation was gathered (Kurganova and Lopes de Gerenyu, 2008). To amend the existing information, own investigations were carried out on main soil type: *Albeluvisols* (Sod-podzolic soil, Vladimir region; 55°49'N, 40°31'E), *Luvic Phaeozems* (Grey forest soil, Moscow region, 54°50'N37°37'E), *Haplic Chernozems* (Ordinary chernozem, Rostov region; 47°27'N, 39°35'E), and *Kashtanozems* (Chestnut soil, Volgograd region; 48°31'N, 43°37'E). 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). Content of C in modern arable soil (zero-moment) was compared with that in soils abandoned 12 yr ago (*Albeluvisols*), 2, 6, 11, 26 yr ago (*Luvic Phaeozems*), 5, 10, 20, 76 yr ago (*Chernozems*) and 15 yr ago (*Kashtanozems*). Soil samples were taken in each soil profile to the depth of 50–60 cm in 10 cm increments (three replicates). The SOC pool (SOC_(t), g C m⁻²) was calculated taking into account the C_{org} content and bulk density of each horizon as follows:

$$\text{SOC}_{(t)} = C_{\text{org}} \text{BD} h, \quad (1)$$

where C_{org} (g C kg⁻¹ of soil) is the SOC fraction of the soil, BD (kg m⁻³) is the soil bulk density and *h* (m) is the depth of the soil core. To allow the comparison of all selected sites, we focused on the SOC-pool of the first 20-cm depth of soil, because it is mostly changed after conversion of arable land to natural vegetation. The 'average carbon accumulation rate' (*R*_{CA}, g C m⁻² yr⁻¹) was calculated according to the following formula:

$$R_{\text{CA}} = (\text{SOC}_{(t)} - \text{SOC}_{(0)})/t, \quad (2)$$

where SOC_(t) and SOC₍₀₎ are the SOC pools in the first 20-cm soil depth of abandoned (restoring) and arable soils (g C m⁻²), respectively; *t* is the period of abandonment (yr).

2.3. Approaches for assessment of total carbon accumulation on Russian territory

Three different approaches (approximation, soil-geoinformation system (soil-GIS) and modelling) were used to estimate the total amount of C sequestered in Russian soils (first 20-cm depth of soil) after 1990 due to the conversion of arable to natural vegetation. 'Approximation approach' is the roughest method of estimation: the total area of former arable lands (30.2 M ha) is merely multiplied by the mean *R*_{CA} during the first 15 yr after LUC. Available data allowed us also to perform the calculations

taking into account various rates of carbon accumulation in different soil types, as well as the different relative contributions of main soil types to the total area of cultivated lands in various regions of Russia.

Using the soil-GIS-approach, we calculated areas of croplands (Yanvareva, 1989) in each administrative region of Russia (Mikhailenko and Bobkov, 1988) as related to the type of soil. All soils indicated in the legend to Soil Map of Russian Federation (Fridland, 1988) were combined into five large groups: (1) *Albeluvisols*, (2) *Phaeozems*, (3) *Chernozems*, (4) *Kashtanozems* and (5) other soils. The official statistic data (Federal Agency of Real Estate Cadastre, 2006) and two different methods were used to estimate the areas of former arable soils, which belong to five groups in each administrative region of Russia. First one (equal proportions) assumed that the abandonment of former arable soils was independent on fertility (type of soil), while the second one (differentiated) supposed that less fertile soils were abandoned at first.

The third, 'modelling approach' was based on the use of our logarithmic models that were developed earlier for estimation of the *R*_{CA} in soils as a dependent on the abandonment period (Kurganova and Lopes de Gerenyu, 2008, 2009; Kurganova et al., 2008). In this case, the areas of abandoned lands were taken into account differently for each year in the interval from 1990 to 2006.

3. Results

3.1. Carbon balance of abandoned lands

Botanical survey showed clearly that the vegetation of former arable lands changed to permanent grasslands after 5–8 yr of abandonment. Shown in Fig. 1a, values of ANP varied from 106 g C m⁻² yr⁻¹ in the former arable land after 1 yr after abandonment to 363 g C m⁻² yr⁻¹ in a 13-yr cut grassland. BNP-value was also the lowest in 1-yr plot (223 g C m⁻² yr⁻¹) and the highest in the former arable land after 10 yr after abandonment (747 g C m⁻² yr⁻¹). The NPP values were equivalent to the sum of ANP and BNP and increased from 330 g C m⁻² yr⁻¹ in 1-yr plot to 1103 g C m⁻² yr⁻¹ in the 10-yr uncut grassland (Fig. 1b). The differences in NPP obtained between studied sites were caused by various botanical compositions of vegetation in postagrogenic ecosystems as well as a difference in weather conditions in 2004 and 2007. Mean annual air temperature (*T*_a) and precipitation during spring-summer (Pss) in 2004 were close to mean annual values for two last decades, while 2007 was significantly warmer (*T*_a = 7.1 °C versus average value of *T*_a = 5.5 °C) and much dryer: precipitation during spring and summer seasons in 2007 amounted 231 mm versus average Pss = 365 mm.

A significant difference in total soil CO₂ fluxes from various post-agrogenic ecosystems was observed. Since the share of root respiration in the TSR of grasslands averaged to 36% for

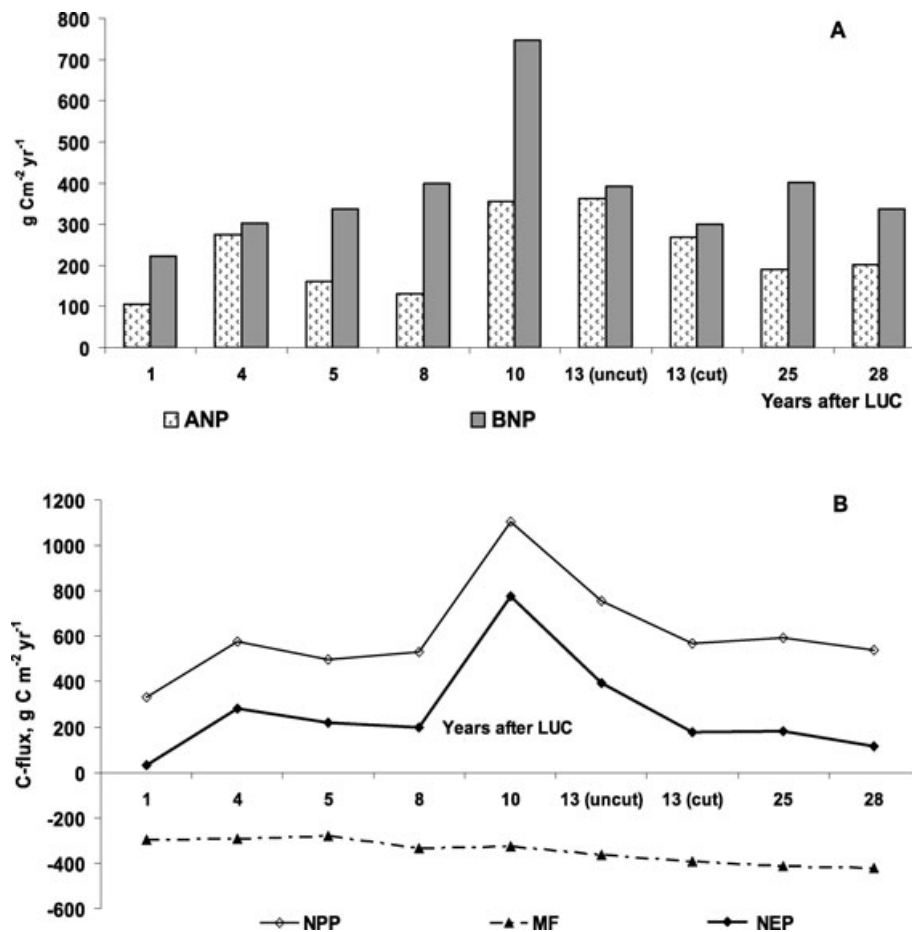


Fig. 1. Carbon fluxes in post-agrogenic ecosystems after different period of land use change (LUC): (A) ANP, aboveground net production; BNP, belowground net production; (B) NPP, net primary production; MF, soil microbial flux of CO₂ and NEP, net ecosystem production.

the summer season (June–August) and 24% beyond the summer (Larionova et al., 2003b), we found that MF of former croplands varied from -294 to -422 g C m⁻² yr⁻¹ depending on the period of abandonment (Fig. 1b). The results obtained indicated clearly that post-agrogenic ecosystems act as a carbon sink, and their NEP changed between 32 and 778 g C m⁻² yr⁻¹ depending on the period after LUC. The average NEP in post-agrogenic ecosystems of Moscow region was 233 ± 48 g C m⁻² yr⁻¹ in dry 2007 and reached 302 ± 164 g C m⁻² yr⁻¹ in 2004 that was close to typical.

3.2. Estimates of changes in the total pool of organic carbon in Russian soils after 1990

Based on our field studies and literature data, we have estimated the R_{CA} for the main soil types (Albeluvisols, Phaeozems, Chernozems and Kastanozems) after the LUC from arable to natural vegetation. These rates varied between 28 and 484 g C m⁻² yr⁻¹ depending upon soil type and the period of abandon-

ment. As a rule, the C accumulation rate was higher during the first years after LUC. The relationship between R_{CA} and the period of abandonment (P) was satisfactorily described by a negative logarithmic function except *Kastanozems* (Table 1). Post-agrogenic ecosystems located on *Kastanozems* were poorly distinguished in rate of carbon accumulation because the period of abandonment was 12–45 yr and we failed to find any data on young abandoned lands where R_{CA} are expected to be much higher. This is an explanation why the logarithmic model developed for R_{CA} approximation for *Kastanozems* was insignificant and characterized by the lowest values of the free term and increment.

It was also found that the mean C accumulation rate in topsoil (first 20-cm depth of soil) during the first 15 yr after abandonment changed from 66 ± 24 g C m⁻² yr⁻¹ in *Kastanozems* to 175 ± 52 g C m⁻² yr⁻¹ in *Chernozems* (Table 2). Since post-agrogenic ecosystems on *Kastanozems* were not young (until 10 yr old) and were located mainly in arid regions of Russia with slow process of humification, they were characterized by

Table 1. Logarithmic models for approximation of carbon accumulation rate (R_{CA} , g C m⁻² yr⁻¹) for the first 20-cm depth of soil in the main soil types depending on the period after LUC (P , yr)

	Type of soil				General
	<i>Albeluvisols</i>	<i>Phaeozems</i>	<i>Chernozems</i>	<i>Kastanozems</i>	
Model	$-54\ln P + 238$	$-60\ln P + 261$	$-70\ln P + 317$	$-17\ln P + 111$	$-53\ln P + 250$
n	5	10	18	6	41
R^2	0.89 ^a	0.74 ^a	0.71 ^a	0.21 ^b	0.63 ^a

^aModel is significant at $F < 0.01$.

^bModel is insignificant.

Table 2. Average carbon accumulation rate in 0–20 cm layer ($R_{CA} \pm SE$, g C m⁻² yr⁻¹; 95% confidence interval) in main soil types for different time periods after LUC (yr)

Period after LUC (yr)	Type of soil				General average
	<i>Albeluvisols</i>	<i>Phaeozems</i>	<i>Chernozems</i>	<i>Kastanozems</i>	
1–15	131 ± 13	134 ± 36	175 ± 52	66 ± 24	132 ± 21
16–30	46 ± 7	67 ± 11	89 ± 30	–	67 ± 9
>30	39 ± 1	58 ± 19	36 ± 4	–	43 ± 4

Table 3. The estimation of total carbon accumulation (Tg of C) in soils of the Russian Federation during 1990–2006 according to different approaches

Approach	Approximation	Soil-GIS	Modelling	General average
General	635	–	440	538 ± 98
Equal proportions	596	694	468	586 ± 65
Differential	524	601	426	517 ± 51
Average	585 ± 33	648 ± 47	445 ± 12	548 ± 35

Note: See short approach descriptions in the text.

the lowest rate of SOC accumulation. Due to the high variability of R_{CA} in soil types, the average values were not significantly different within the region studied.

General average values of R_{CA} were 132 ± 21 and 67 ± 9 g C m⁻² yr⁻¹ for the first 15 yr of abandonment and for the next 15 yr, respectively. For the soils with longer period of restoration (>30 yr), the average R_{CA} was three-fold lower (43 ± 4 g of C m⁻² yr⁻¹) as compared to R_{CA} during the first 15 yr of abandonment.

Using three different approaches, we have demonstrated that the changes in land use system after 1990 caused an appreciable C-sequestration in Russian soils, which varied between 426 and 694 Tg C during 1990–2006 in the first 20-cm depth of soil (Table 3). Assuming that the calculation methods used were equally substantiated, the carbon accumulation in former arable soils of Russia (30.2 million ha) averaged 548 ± 35 Tg of C (or 34 ± 2.2 Tg of C yr⁻¹). The uncertainty of this estimation caused by different calculation methods is about 8%.

3.3. Updated assessment of carbon balance on Russian territory

In recent years, the carbon balance estimate for Russian territory was of interest for experts since it plays an important role in global carbon cycling. The baseline estimations (relating to 1990) of total NPP and MF for Russian terrestrial ecosystems amounted to 4.41 (Voronin and Black, 2005) and 2.78 Pg C yr⁻¹, respectively (Kurganova, 2003). Non-soil sources of CO₂ (fossil fuel, forest fires and diseases, debris decomposition, agricultural, timber and peat extraction, etc.) were estimated at 0.80 Pg C yr⁻¹ from 2002–2006 (Table 4). Obviously among the non-soil sources of CO₂, the fossil fuels and cement emissions, debris decomposition, and agriculture are the most important since they amounted 91.2% of total anthropogenic emission of CO₂. The other non-soil CO₂ sources are inside the error of estimations.

Table 4. Non-soil CO₂ emission from Russian territory in 2002–2006

Source	CO ₂ -C, Tg yr ⁻¹	% to total
Fossil fuels and cement ^a	409	51.5
Debris decomposition ^b	214	26.4
Agricultural production ^c	108	13.3
River discharge (soluble C) ^d	21.8	2.7
Timbering ^c	18.6	2.3
Forest fires ^c	12.0	1.5
Forest post fire emission ^c	12.0	1.5
Forest deceases ^c	2.70	0.30
Peat extraction ^c	2.03	0.30
Leaching of soil carbonates ^e	1.00	0.01
Soil liming ^c	0.36	0.05
Total	801	100

^awww.global.carbonproject.org.^bZamolodchikov (2009).^cFederal State Statistics Service (2009).^dVinogradov et al. (1999).^eKudeyarov et al. (2007).

According to our calculations, changes in land use system after 1990 caused an additional sink of C to post-agrogenic ecosystems on Russian territory that averaged 74 ± 22 Tg C yr⁻¹. Therefore, the results obtained demonstrate that the Russian territory currently acts as an absolute sink for atmospheric CO₂ at the rate of about 903 Tg C yr⁻¹ (or 0.90 Pg C yr⁻¹). The uncertainty of C-balance estimation presented in this study is high and exceeds 50% since according to Nilsson et al. (2000), the uncertainty of main carbon fluxes forming C-budget on Russian territory varied between 5 and 40%.

4. Discussion

Our data on NEP in post-agrogenic ecosystems of deciduous forest zone agree with the results on carbon balance (net ecosystem exchange, NEE) estimated by micrometeorological measurements in former arable lands of the steppe region in Russia (Belelli Marchesini, 2007). It was shown that the post-agrogenic ecosystems in the Khakassia (East Siberia, Russia) acted as a CO₂ sink as well: the NEE varied from 210 g C m⁻² yr⁻¹ at the early stage (5 yr of abandonment) to 114 g C m⁻² yr⁻¹ at a mature stage and average value of NEE was 151.7 ± 30.1 g C m⁻² yr⁻¹ (Belelli Marchesini et al., 2007). Our data accord with the first results obtained within the framework of the European Green Grass project as well (Soussanna et al., 2004). It was shown that the grasslands situated in 10 different European countries also acted as CO₂ sink with NEE varying from 50 to 550 g C m⁻² yr⁻¹.

According to our calculations, the extra CO₂ sink into post-agrogenic ecosystems averaged 245 ± 73 g C m⁻² yr⁻¹ for the first 15 yr after LUC from arable to permanent grassland, and

NEP for the total area of abandoned lands on Russian territory (30.2 million ha) may be estimated at 74 ± 22 Tg C yr⁻¹ due to the changes in land use system after 1990. Therefore, the conversion of low-fertile arable lands to natural vegetation can be a good alternative to artificial reforestation for the sequestration of additional atmospheric carbon dioxide in NEP of post-agrogenic ecosystems.

The analysis of the available literature data on C recovery after conversion of cultivated land to natural vegetation showed that results obtained in this study well agree with the data of other specialists. In the United States of America, abandoned lands under the Conversation Reserve Program have also acted as sinks for atmospheric CO₂, accumulating C at an average rate up 110 g C m⁻² yr⁻¹ (Gebhart et al., 1994). Post and Kwon (2000) found that the maximal rate of the carbon accumulation was observed at the early restoration stages, but it did not exceed 100 g of C m⁻² yr⁻¹. In the tropics, upon the natural forestation of former agricultural lands, the rate of the carbon accumulation during the first 20 yr averaged 130 g of C m⁻² yr⁻¹; in the following 80 yr, it was 41 g of C m⁻² yr⁻¹ (Silver et al., 2000). However, our estimates of R_{CA} in soils of the European part of Russia are higher than the general mean values ($33\text{--}34$ and 57 ± 14 g C m⁻² yr⁻¹) cited in reviews by Post and Kwon (2000), and West and Post (2002). The difference in the results obtained may be explained by the existence of very young abandoned lands (2–5 yr old) with a high R_{CA} among our study sites while the age of the majority of experimental sites that were presented in above mentioned reviews exceeded 15 yr. It was also found that total stock of SOC in the former arable layer has increased approximately 5% from the early 1990s. It should be noted that the soil organic matter accumulated in post-agrogenic ecosystems forms the NBP, which is long lasting C-stock with a carbon lifetime much longer than in ‘Kyoto forests’.

The first rough estimate of total C accumulation in the Russian territory due to LUCs after 1990 was done by Larionova et al. (2003a). It was based on the limited experimental data on R_{CA} and comprised 660 Tg C for an area of 34 million ha and for the period from 1990 to 2002 (Table 5). Vuichard et al. (2008) estimated the total C accumulation for the territory of the former USSR using the ‘Orchidee’ model. According to their calculations, the total C accumulation was much lower and amounted to 64 Tg C for the period between 1991 and 2000. The use of RothC model allowed to conclude that the C sequestration in the former cultivated lands of Russia was 248 Tg C during 1990–2005 (Romanovskaya, 2008). The large difference between the estimates of total C-sequestration in Russian soils after 1990 are governed by differences in methodology approaches, areas of abandoned arable lands, time periods that were used for calculation, and limited experimental data on changes in C-stock after conversion of arable to natural vegetation in Russia (Table 5). On the assumption that the area of abandoned lands is above or equal 30 million ha in 2005–2006 and modelling approach is the most reasonable, we may consider that total SOC accumulation

Table 5. Carbon sequestration in the former arable lands of Russia due to LUC after 1990 according to different estimates

Period	Territory	Area (M ha)	Approach	C accumu-lation (Tg C)	Reference
1990–2004	Russia	34.0	Approximation	660	Larionova et al. (2003a)
1990–2005	Russia	27.9	RothC-model	248	Romanovskaya (2008)
1990–2006	Russia	30.2	Soil-GIS, modelling	426–694	This study
1991–2000	Former USSR	20.0	Orchidee-model	64	Vuichard et al. (2008)

in Russian soils due to LUC after 1990 ranges between 250 and 450 Tg C, as most realistic values.

The results obtained have shown that the post-agrogenic ecosystems in Russia provide the additional C-sink in NEP and NBP (108 Tg C yr⁻¹) that could annually compensate for all the CO₂ emitted from agricultural activity or about 25% of the current fossil fuel emissions in the Russian Federation. In the United States of America, the conversion of croplands to conservation tillage, including no-till practices, during 30 yr could sequester all the CO₂ emitted from agricultural activities and up to 1% of fossil fuel emission (Kern and Johnson, 1993).

We consider that the assessments presented in this study can have a considerable impact on the Kyoto implementation policies since they clearly describe the C-accumulation processes in Russian soils caused by recent LUC. It has been suggested that the sequestration of atmospheric carbon dioxide in soil organic matter could contribute significantly in attempts of Russia to adhere to the Kyoto protocol.

5. Conclusions

Changes in Russian land use system after 1990 that displayed significant areas of abandoned croplands have governed the substantial shifts in carbon balance (NEP) and total SOC pool (NBP) on the territory of the Russian Federation. Our results showed that after 4–5 yr of abandonment, the former croplands acted as a stable sink of carbon. The extra C-sink to the post-agrogenic ecosystems (NEP) averaged $245 \pm 73 \text{ g C m}^{-2} \text{ yr}^{-1}$ for the first 15 yr after the LUC. For the total area of abandoned lands on Russian territory (30.2 million ha), additional sink of CO₂ in NEP amounted to $74 \pm 22 \text{ Tg C yr}^{-1}$. Currently, Russian territory acts as an absolute sink of atmospheric CO₂ at a rate of about 0.90 Pg C yr⁻¹.

Using three different approaches, we demonstrated that the changes in land use system after 1990 have governed the appreciable carbon sequestration in Russian soils (first 20-cm depth of soil) to an average of $548 \pm 35 \text{ Tg C}$ during 1990–2006 (or $34 \text{ Tg of C yr}^{-1}$). Organic matter stock in the former arable layer has increased by about 5% since the 1990s. SOC accumulated in post-agrogenic ecosystems is long lasting C-stock and forms NEB, where carbon lifetime is much longer than in ‘Kyoto forests’. The sequestration of atmospheric carbon dioxide in soil organic matter could contribute substantially in attempts of Russia to adhere the Kyoto protocol.

6. Acknowledgments

This study was supported by Russian Foundation for Basic Researchers (Projects NN 07–04–01333, 08–04–01619) and Program 16 of RAS. Authors appreciate deeply Dr. Alexander Yermolaev for his assistance in botanical study, Dr. Tatiana Myakshina and Dr. Dmitry Sapronov for soil respiration measurements, Dr. Valentina Lichko, and students of Leipzig University (Germany) and Voronezh University (Russia) for their help in NPP determination in post-agrogenic ecosystems. We are very thankful to Eric S. Drews (Portland, USA) for his comments and editing of manuscript.

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