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Large-scale carbon sequestration in post-agrogenic ecosystems in Russia and Kazakhstan

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ABSTRACT

Most land use changes (LUC) significantly affect the amount of carbon (C) sequestered in vegetation and soil, thereby, shifting the C balance in ecosystems. Disintegration of the USSR and the followed collapse of collective farming system have led to abandonment of more than 58 million ha (Mha) of former croplands in Russia and Kazakhstan that comprise together about 90% of land area in the former USSR. This was the most widespread and abrupt LUC in the 20th century in the northern hemisphere. The spontaneous withdrawal of croplands in 1990s caused several benefits for environment including substantial C sequestration in post-agrogenic ecosystems. The new estimations of net ecosystem production (NEP) and changes in soil organic carbon stocks (Δ*SOC*) in post-agrogenic ecosystems presented here are based on the uniform bio-climatic approach, and hereby, allow to update C balance of the former USSR. The total extra C sink in abandoned croplands in Russia (45.5 Mha) and Kazakhstan (12.9 Mha) is estimated to be 155 ± 27 Mt C yr^{-1} and 31 ± 2 Mt C yr^{-1}, respectively. This additional C sink could cover about 18% of the global CO_2 release due to deforestation and other land use changes or compensate annually about 36% and 49% of the current fossil fuel emissions in Russia and Kazakhstan, respectively. The extra C sink to the post-agrogenic ecosystems in Russia and Kazakhstan contributes possibly about 1/3 part to the total current C balance of the former USSR. Hence, the disintegration of the former USSR significantly affected national and global C budget over few decades after LUC.

1. Introduction

Most land use changes (LUC) significantly affect the amount of carbon (C) sequestered in vegetation and soil, thereby, shifting the C balance in ecosystems (Houghton, 2010). The greatest C fluxes caused by LUC are attributed to conversion of croplands to native vegetation and vice versa (Houghton and Goodale, 2004; Schlesinger, 1986). A large number of reviews and experimental studies report that abandoned agricultural land (remaining without cultivation) will be occupied by natural vegetation, that lead to organic C accumulation both in soil (Guo and Gifford, 2002; Kalinina et al., 2011, 2013, 2015; Kurganova and Lopes de Gerenyu, 2008, 2009; Lyuri et al., 2010) and in vegetation (Kurganova et al., 2007, 2008; Pérez-Cruzado et al., 2011; Post and Kwon, 2000).

The magnitude of annual C sink in soil and vegetation varies widely and depends on the intensity of previous land use, soil type (or fertility), and climate (Johnson and Curtis, 2001; Kurganova et al., 2010b, 2014; Uhl et al., 1988). The rates of C accumulation in mineral soils are rather modest especially in comparison with much faster rates of C accumulation in vegetation, surface litter, or woody debris (Barford et al., 2001; Hooker and Compton, 2003; Kalinina et al., 2010). Based on global meta-analysis, Post and Kwon (2000) indicated that the average rate of C accumulation in soil is about 0.33 Mg C ha^{-1} yr^{-1} for grassland and forest establishment. According to IPCC report (2000), the conversion of arable land to grassland resulted in build-up of C stocks at rate of 0.5 Mg C ha^{-1} yr^{-1} over 50 years (range 0.3–0.8 Mg C ha^{-1} yr^{-1}). Soussana et al. (2004) estimated the average rate of C sequestration due to conversion of cropland to grassland to be 0.49 ± 0.26 Mg C ha^{-1} yr^{-1} for a 0–30 cm soil layer over first 20 years after LUC. In temperate climate, grassland establishment caused a long lasting C sink with average change of C stock of 39.8 ± 11.0% relatively to the initial level in the 30-cm topsoil over first 20 yrs. The afforestation on former croplands for the same period after LUC induced C sink of 22.4 ± 10.4% of initial level both in forest floor and in mineral soil (Poeplau et al., 2011). The C re-accumulation in soil usually lasts some decades and new equilibrium can be reached after 80–120 years (Poeplau et al., 2011; Soussana et al., 2004). Globally, C accumulation in mineral soils recovering from past tillage amounts for about 0.1 Pg C yr^{-1} (Post and Kwon, 2000).

Critical changes in land use caused by disintegration of the USSR, followed by economic crisis and abrupt shifts in agricultural policy, took place in the end of last century. The collapse of the Soviet farming system in early 1990s led to radical decrease of cropland area both in

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Russia and in Kazakhstan — the largest republics in the former USSR. Together they occupied 88.3% of its total land area and over 1/8th of the global one. Between 1990 and 2007, about 45.5 Mha of arable lands were abandoned in Russia (Lyuri et al., 2010) and 12.9 Mha of former croplands were abandoned in Kazakhstan (Morgounov and Trethowan, 2008). Considering that the total cultivated area in both countries in 1990 comprised 141.8 Mha, more than 40% of former croplands were withdrawn from agriculture for less than two decades. This was the most widespread and abrupt LUC in the 20th century in the northern hemisphere (Henebry, 2009; Lyuri et al., 2010).

Total soil organic carbon (SOC) stock for Russia and Kazakhstan (upper 100 cm soil layer, including peat soils) exceeded 1/5 of the world SOC pool (Rojkov et al., 1996). Therefore, their C stocks are a major contribution to the global one (Kurganova et al., 2010a; Kurganova and Kudeayrov, 2012). Over the last decade, several studies (Kurganova et al., 2010a, 2014; Larionova et al., 2003a; Romanovskaya, 2008; Schierhorn et al., 2013; Vuichard et al., 2008) were aimed to estimate the total C sequestered in Russian soils due to the croplands abandonment. The application of various approaches and discrepancy within areas of abandoned lands and rates of C sequestration resulted in the significant variability of previous estimations of total changes in C stocks in Russian soils after LUC: from 0.47 to 1.29 Mg C ha^{-1} yr^{-1}. The early estimate of additional C–CO_2 sink from atmosphere in Russian post-agrogenic ecosystems (or net ecosystem production, NEP) was based on few studies conducted in deciduous forest and steppe regions (Kurganova et al., 2010a). There was lack of data on NEP estimates for taiga zone and extra C sink due to spontaneous reforestation was underestimated. Therefore, our first estimation of total NEP in Russian abandoned lands seems rather rough — about 74 ± 22 Tg C yr^{-1} (Kurganova and Kudeayrov, 2012; Kurganova et al., 2010a) and should be updated taking into account new experimental studies carried out during last 5–7 years. For Kazakhstan such estimations were not performed at all.

In this study, for the first time we assessed the shift in total SOC stocks and additional C sink in post-agrogenic ecosystems induced by the collapse of farming system after 1990 in Russia and Kazakhstan, which together occupied about 90% of land area in the former USSR. Our new estimations of NEP and changes in SOC stocks in post-agrogenic ecosystems are based on the uniform bio-climatic approach, and hereby, allow us to update C balance of the former USSR. Firstly, we compiled all available literature data reporting the changes in NEP and SOC stocks in the young post-agrogenic ecosystems of Russia and Kazakhstan. Secondly, the national estimates of the C recovery caused by the farming system collapse in Russia and Kazakhstan were correlated to the current fossil fuel emissions in these countries and compared to the total C loss due to global LUC.

2. Materials and methods

2.1. Estimation of SOC stocks changes due to conversion of croplands to natural vegetation

All available data on SOC stock changes in soils (upper 20-cm layer) after conversion of former arable lands to natural vegetation were collected (Kurganova et al., 2014). The annual rates of SOC accumulation (ΔSOC, Mg C ha^{-1} yr^{-1}) for the first 20 yrs of post agrogenic evolution were clustered in four main reference soil groups (Word Reference Base for Soil Resources, 2014): *Retisols* (*RE*), *Luvisols* (*LV*), *Chernozems* (*CH*), and *Kastanozems* (*KS*), which are most representative soils under croplands in taiga, deciduous forest, forest and central steppes, and southern steppe regions, respectively (Fridland, 1988). These four reference groups occupied about 85% of total agricultural area in Russia before 1990 (Nilsson et al., 2000). All other soils remained (*Umbrisols*, *Cambisols*, *Podzols*, *Fluvisols*, *Gleysoils*, *Planosols*, *Regosols*, *Arenosols*, *Solonetzes*) occupied 15% of agricultural lands, not associated with four reference groups due to their specific properties and formed the fifth group termed "other soils" (os).

Table 1
Changes in SOC stocks in post-agrogenic ecosystems of bio-climatic regions of Russia and in Kazakhstan during the first 20 yrs after LUC[a].

Bio-climatic zone	Main soil types[b]	n[c]	Range of ΔSOC[d], Mg C ha^{-1} yr^{-1}	Mean ΔSOC ± SE, Mg C ha^{-1} yr^{-1}
European Russia				
Middle & southern taiga	RE, LV	47	−0.23–2.41	0.90 ± 0.09
Deciduous forest & forest steppe	LV, CH	47	−0.08–3.70	1.20 ± 0.11
Steppe	CH, KS	25	0.25–3.70	1.22 ± 0.17
Asian Russia	RE, LV, CH, KS, os	85	−0.23–3.70	0.96 ± 0.08
Kazakhstan				
Dry steppe & semi-desert	KS	6	0.42–1.38	0.93 ± 0.138

[a] Adapted from Kurganova et al. (2014).
[b] Four main soil groups according to Word Reference Base for Soil Resources (2014) are: RE = Retisols, LV = Luvisols, CH = Chernozems, KS = Kastanozems, and os = other soils.
[c] Number of observations.
[d] ΔSOC was estimated for upper 20-cm of mineral soil.

The data on annual rate of SOC stock changes in main soil groups (Kurganova et al., 2014) were summarized according to the following bio-climatic regions: (i) middle & southern taiga, MST (ii) deciduous forest & forest steppe, DFS (iii) steppe, ST, and (iv) dry steppe & semi-desert, DS. The average annual ΔSOC for each bio-climatic region was estimated, considering the prevalence of main soil groups in each region (Table 1). We assumed that in European part of Russia,[1] dominant soil types in the middle and southern taiga were RE and LV, in the deciduous forest and forest steppe regions — LV and CH, in the steppe area — CH and KS, and in the dry steppe and semi-desert of Kazakhstan — KS.

2.2. Estimation of NEP values in post-agrogenic ecosystems

The net ecosystem production (or C balance) in terrestrial ecosystems can be estimated by two main ways: (1) as the difference between the net primary production (NPP) and the CO_2 released by soil microbial respiration (MR), and (2) directly by the use of the eddy-covariance method. Positive NEP values indicate CO_2 sink in the ecosystem, while negative ones suggest that the ecosystems act as a source of CO_2. To estimate NEP values of abandoned lands in deciduous forest regions, we used experimental data of our previous investigations in Moscow region (7 sites). The detailed description of methodology and results were presented earlier (Kurganova et al., 2007, 2008). The average NEP values in young post-agrogenic ecosystems amounted for 2.96 ± 0.90 Mg C ha^{-1} yr^{-1} (Table 2). In southern taiga, main components of C balance were determined in young birch and pine forests (2–23 yrs old) overgrowing on former croplands. According to Gulbe (2009) and Bazilevich (1993), average NPP values accounted for 5.37 ± 0.66 Mg C ha^{-1} yr^{-1} and 1.04 ± 0.28 Mg C ha^{-1} yr^{-1} for frees and herbs in young forest ecosystems, respectively (Table 2). Total soil respiration (SR) in post-agrogenic ecosystems of South taiga varied between 4.38 and 6.77 Mg C ha^{-1} yr^{-1} (Lyuri et al., 2013; own unpublished data). Microbial respiration of soils was estimated as 2/3 parts of total SR (Kurganova et al., 2008; Larionova et al., 2003b) and mean MR value in southern taiga region comprised 4.06 ± 0.31 Mg C ha^{-1} yr^{-1} (Table 2). The direct determinations of NEP values were carried out in the post-agrogenic ecosystems in steppe region (Khakassia, Russia; Belelli Marchesini et al., 2007) and in dry steppe

[1] European part of Russia includes the following regions: North-Western, Central, Volga-Vyutsky, Central-Chernozemny, Povolzhsky, North-Caucasian, and Ural excepting Kurgan and Sverdlovsk districts (Lyuri et al., 2010).

Table 2
Main components of carbon balance and NEP values in post-agrogenic ecosystems of bio-climatic regions of Russia and in Kazakhstan.

Bio-climatic zone	Age, yrs	Parameters	n[a]	Range, Mg C ha^{-1} yr^{-1}	Mean value, Mg C ha^{-1} yr^{-1}	Reference
European Russia						
Middle & southern taiga	2–13	NPP[b]	13	1.16–9.22	5.37 ± 0.66	Gulbe (2009);
	<20	NPP[c]	6	0.58–2.42	1.04 ± 0.28	Bazilevich (1993);
	4–10, 23	MR	8	2.92–4.51	3.84 ± 0.24	Lyuri et al. (2013); Present study
Deciduous forest & forest steppe	2–15	NEP	7	0.32–7.78	2.96 ± 0.90	Kurganova et al. (2007, 2008)
Steppe	5, 10	NEP	2	1.46–2.01	1.74 ± 0.28	Belelli Marchesini et al. (2007)
Asian Russia	–	NEP	10	0.32–7.78	2.33 ± 0.42	Present study
Kazakhstan						
Dry steppe & semi-desert	<20	NEP	1	–	1.46	Perez-Quezada et al. (2010)

[a] Number of plots/observations.
[b] NPP of trees in young forest.
[c] NPP of herb cover in young forests.

(Astana region, Kazakhstan; Perez-Quezada et al., 2010). The NEP values varied here between 1.46 and 1.74 Mg C ha^{-1} yr^{-1} (Table 2).

2.3. Approaches for regional and national estimations

Bookkeeping models were used to estimate the changes in SOC stocks and C balance due to the land use changes. These models are typical to calculate annual CO_2 emissions and C accumulations at various scales — from the regional level to national or global (Canadell et al., 2007; Shvidenko and Nilsson, 2003, 2011). Two types of information are required (IPCC, 2013): areas of land use change (e.g., due to croplands or grassland transition) and per-hectare changes in C stocks/fluxes following LUC. These models generally consider only C fluxes or pools resulting from LUC, but do not include the indirect effects of climate and human-induced changes, such as CO_2 or nitrogen deposition.

The distribution area of post-agrogenic ecosystems in various bioclimatic regions of European Russia (middle & southern taiga, deciduous forest & forest steppe, and steppe), the total area of abandoned lands in Asian Russia (Lyuri et al., 2010), and Kazakhstan (Morgounov and Trethowan, 2008) were taken into account to calculate the total NEP and changes in SOC stocks after massive croplands withdrawal in the former USSR. According to estimates presented by Lyuri et al. (2010), about 58% of the total abandoned area (~33.9 Mha) is located in the European Russia and the shares of Asian part of Russia and Kazakhstan in total area are approximately the same (20–22%). Therefore, to estimate the total amount of C sequestered in Russian and Kazakhstan soils after conversion of croplands to natural vegetation, we considered the average C accumulation rate and the area distribution of post-agrogenic ecosystems for various bio-climatic regions. NEP values were also estimated separately: for each bio-climatic region in the European Russia and dry steppe & semi-desert area in Kazakhstan. Whereas the boundaries between bio-climatic regions in Asian part of Russia were unclear, average values of *ΔSOC* and NEP across all bio-climatic regions of European Russia were applied for future calculations.

2.4. Statistical analysis

Average values and standard errors are presented in the tables and figures. The overall uncertainty around the estimate of total soil C sequestration in Russia and Kazakhstan is mainly affected by the precision of experimental data on C accumulation rate and NEP values. We assume that the total areas of abandoned cropland remain nearly constant after 2005–2007 (45.5 Mha in Russia and 12.9 Mha in Kazakhstan). Therefore, the uncertainty of estimation for total C sequestration (*ΔSOC*) and NEP values was determined by standard error for C accumulation rates considering the total area of abandoned lands in various bio-climatic regions of Russia or total area for Kazakhstan.

3. Results

3.1. Changes in SOC stocks due to abandonment of arable lands

The abandonment of croplands and succession of natural vegetation has induced generally the build-up of SOC stocks in all bioclimatic regions of Russia and Kazakhstan. Average rate of soil organic carbon changes (*ΔSOC*) in uppermost mineral soils (0–20 cm) during the first 20 yrs after land abandonment did not differ significantly in various bio-climatic regions (Fig. 1). *ΔSOC* values were the highest in deciduous forest, forest steppe, and steppe areas (1.20–1.22 Mg C ha^{-1} yr^{-1}) and the lowest were in taiga regions of Russia and dry steppe of Kazakhstan (0.90–0.93 Mg C ha^{-1} yr^{-1}). For Asian part of Russia the rate of C sequestration was 0.96 ± 0.08 Mg C ha^{-1} yr^{-1} (general average for dataset).

The average C accumulation rate in main soil types of Russia decreased strongly over 20–50 years after land abandonment (Fig. 2). The relationship between *ΔSOC* and the period of abandonment was satisfactorily described by negative logarithmic function and a new equilibrium of SOC stock can be reached not earlier than after 30–40 yrs.

Total SOC sequestration due to the conversion of croplands to natural vegetation amounted to 48.8 ± 5.4 Mt C yr^{-1} and 12.0 ± 1.7 Mt C yr^{-1} in Russia and Kazakhstan, respectively (Table 3). Post-agrogenic soils of the steppe region of Russia contribute about 28% to the total extra C stocks in Russia and Kazakhstan, while other regions (middle & southern taiga; deciduous forest & forest steppe) provide about 18–20% of total SOC stocks build-up.

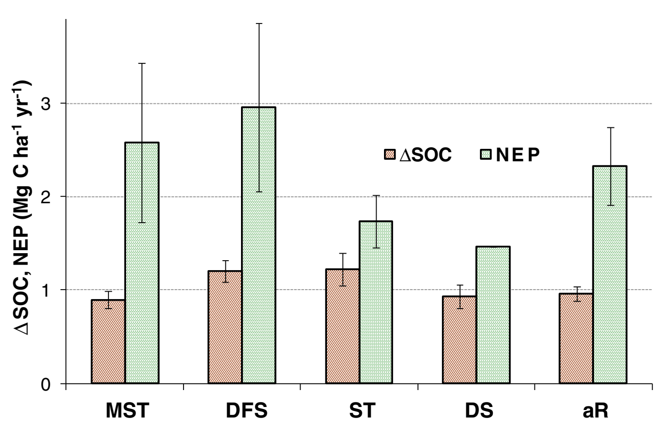

Fig. 1. Average annual changes in SOC stocks and NEP values in main bio-climatic regions for first 20 yrs after conversion on cropland to natural vegetation. The error bars represent the standard error for each region: middle & southern taiga (MST), deciduous forest & forest steppe (DFS), steppe (ST), dry steppe & semi-desert (DS), and Asian part of Russia (aR).

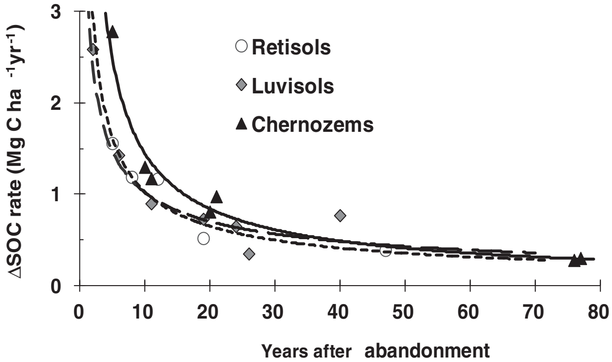

Fig. 2. Temporal dynamics of average *ΔSOC* rate in main soil groups after conversion of croplands to natural vegetation.

3.2. NEP in post-agrogenic ecosystems of various bio-climatic zones

Our results indicated clearly that post-agrogenic ecosystems in deciduous forest and forest steppe regions acted as a significant C sink of atmospheric CO_2: NEP values reached here 2.96 ± 0.90 Mg C ha^{-1} yr^{-1}. In the grassland ecosystems of steppe areas extra C sink induced by cropland abandonment was lower and varied between 1.46 and 1.74 Mg C ha^{-1} yr^{-1} (Fig. 1). Average NEP across various bio-climatic regions for the first 20 years after LUC was 2.33 ± 0.42 Mg C ha^{-1} yr^{-1}, and these values were attributed to Asian part of Russia (Table 2).

The total extra sink of C to vegetation of abandoned lands in Russia (45.5 Mha) and Kazakhstan (12.9 Mha) is estimated to be 106 ± 26 Mt C yr^{-1} and 18.6 Mt C yr^{-1}, respectively. Important is that the process of spontaneous reforestation in post-agrogenic ecosystems of European Russia (taiga, deciduous forest and forest steppe regions) contributes about the half (44%) to the total C sink induced by the croplands abandonment in Russia and Kazakhstan (Table 3).

4. Discussion

4.1. Change in SOC stocks after croplands abandonment in early 1990s

Disintegration of the USSR in 1991 resulted in the economic crisis and changes that affected the agricultural framework (Morgounov and Trethowan, 2008). The collapse of Soviet collective farming system in Russia and Kazakhstan induced an intensive process of croplands abandonment in the early 1990s. Active natural reforestation was typical for the southern taiga, deciduous forest, and forest steppe regions, while the grassland establishment occurred mainly in the steppe area (Lyuri et al., 2010). After establishment of natural vegetation on former arable soils, a permanent plant cover proved the soil organic matter protection and contributed significantly to the process of soil C sequestration (Soussana et al., 2004). The changes in SOC stocks followed plant succession during the post-agrogenic evolution. Our findings are in good agreement with other studies and show clearly more fast C accumulation during first years after abandonment of croplands (Poeplau et al., 2011; Silver et al., 2000; West and Post, 2002). Average estimates of C accumulation rate in various bio-climatic regions for the first 20 yrs after LUC presented in this study seem to be rather high (0.90–1.22 Mg C ha^{-1} yr^{-1}). However, they reasonably demonstrate that arable lands abandoned after 1990 were highly deficient in C due to the fourfold drop of fertilization in early 1990s compared to 1980s (Russia in figures, 2012). Strong reduction of fertilizer application resulted in reduced crop productivity and hence C inputs by roots, rhizodeposition, and aboveground crop residues to the cultivated soils. Furthermore, the C sequestration rates estimated for main bio-climatic regions corresponded well to those reported after conversion of croplands to forest or grassland (0.44–0.92 Mg C ha^{-1} yr^{-1} in the upper 25 cm of mineral soil) presented in recent meta-analysis for temperate regions (Poeplau et al., 2011).

A new equilibrium of SOC stock can be reached after 60–80 yrs or later if management practices tend to be constant and the C input is equal to C–CO_2 release by mineralization of organic matter. The rate of C sequestration in the main soil types can reach the constant level not earlier than after 30–40 yrs of post-agrogenic evolution. This finding is in a good agreement with conclusion of Potter et al. (2000) who observed a linear relationship between the length of grassland establishment and the amount of SOC sequestered in the surface 60 cm layer for time periods from 6 to 60 years. The slope of this function provided an estimate of C sequestration rate, in this case 0.45 Mg C ha^{-1} yr^{-1}, and it required nearly an additional century (98 years) for 60-year grass site to reach the level of SOC stock in native prairie. Recent meta-analyses and simulation results performed by Poeplau et al. (2011) revealed that conversion of croplands to forest or grassland resulted in a long lasting C sink with a relative C stock change of 116–128%. In this case, a new equilibrium SOC level could be reached after 120 yrs.

According to our estimations, organic C stock in former arable layer has increased by nearly 5% of total C stocks in upper 0–20 cm layer of arable soils during first 20 yrs of post-agrogenic evolution (Kurganova et al., 2014). Moreover, the soil C build up due to establishment of natural vegetation occurs much slower than SOC losses after converting of grassland or forest to arable land (Soussana et al., 2004). It should be considered in future if the new idle land expansion might start.

The early estimates of total C accumulation on the Russian territory due to land use changes after 1990 varied widely — from 64 Mt C (Vuichard et al., 2008) to 248–660 Mt C (Larionova et al., 2003a; Romanovskaya, 2008). A large difference between the estimates is governed by differences in calculation approaches, areas of abandoned arable lands, time periods after abandonment considered, and limited experimental data on changes in C-stock after conversion of arable to

Table 3
Total changes in SOC stocks and NEP values in post-agrogenic ecosystems of Russia and Kazakhstan during first 20 yrs after LUC.

Bio-climatic zone	Area[a], Mha	*ΔSOC*, Mt C yr^{-1}	Contribution, %	NEP, Mt C yr^{-1}	Contribution, %	Total C sink, Mt C yr^{-1}
European Russia						
Middle & southern taiga	11.1	9.9 ± 1.0	16	28.6 ± 9.4	23	38.5 ± 9.5
Deciduous forest & forest steppe	8.9	10.7 ± 1.0	18	26.3 ± 8.0	21	37.0 ± 8.1
Steppe	13.9	17.0 ± 2.5	28	24.2 ± 3.9	19	41.2 ± 4.6
Asian Russia	11.6	11.1 ± 0.9	18	27.0 ± 4.9	22	38.1 ± 5.0
Total Russia	45.5	48.8 ± 5.4	80	106 ± 26	85	155 ± 27
Kazakhstan						
Dry steppe & semi-desert	12.9[b]	12.0 ± 1.7	20	18.6	15	30.9 ± 1.7
Grand total	58.4	60.8 ± 5.6	80	125 ± 26	100	185 ± 27

[a] Data were adapted from Lyuri et al. (2010: 154).
[b] Morgounov and Trethowan (2008: 162).

natural vegetation in Russia. Our recent estimation of total C sequestration for Russia for 1990–2009 based on soil-GIS approach amounts for 870 Mt C or 42.6 ± 3.8 Mt C per year (Kurganova et al., 2014) and corresponds well to the results obtained in present study. Most contemporary simulation results presented by Schierhorn et al. (2013) suggested that cropland abandonment in European Russia, Belarus, and Ukraine (total area ~31 Mha) resulted in the net C sink of 470 Mt C for 1990 to 2009. Despite considerable variability of estimations for additional SOC accumulation in Russian soils due to land abandonment, we conclude that the succession of natural vegetation and recovery of soils during post-agrogenic evolution resulted in the significant C sequestration in soils and affect substantially the national C budget (Kurganova and Kudeayrov, 2012; Kurganova et al., 2010a).

4.2. Estimation of carbon budget for Russian Federation and Kazakhstan

The abandonment of agricultural lands resulted in organic C sequestration both in soils and in vegetation. The restoration of natural vegetation during post-agrogenic evolution of former cropland provided essential additional sink in NEP which amounted to 106 ± 26 and 18.9 Mt C yr^{-1} for Russia and Kazakhstan, respectively. Therefore, based on the bio-climatic approach and new experimental studies, we significantly improved our early assessment of total C sink build-up for all Russian territory (74 ± 22 Mt C yr^{-1}; Kurganova et al., 2010a) and firstly estimated the additional C-sink in post-agrogenic ecosystems of Kazakhstan. The spontaneous withdrawal of croplands in the early 1990s provided the additional C sink that could annually compensate about 36 and 49% of the current (level of 2010) fossil fuel emissions in Russia and Kazakhstan (http://www.iea.org), respectively. This extra C sink is equivalent to ~30% of the annual C sink in all Russian forests (Zamolodchikov et al., 2011) and could cover about 18% of the global CO_2 release due to deforestation and other land use changes (Pan et al., 2011).

Russia and Kazakhstan occupy nearly 90% of total area of the former USSR and form the principal part of its C budget. The results obtained here demonstrate that territory of the former USSR provides additional C sink at rate of 186 ± 27 Mt C ha^{-1} and acts obviously as an absolute sink for atmospheric CO_2. Total C balance in Russia, Ukraine, Belarus, and Kazakhstan using inventory-based, eddy covariance, and inversion methods was recently estimated to be −613.5 Mt C yr^{-1} with a wide range from −342 Mt C yr^{-1} to −1350 Mt C yr^{-1} (Dolman et al., 2012). Therefore, extra C sink to the post-agrogenic ecosystems in Russia and Kazakhstan contributes possibly about 1/3 part to the total current C balance of the former USSR.

5. Conclusions

The spontaneous withdrawal of croplands in 1990s caused several benefits for environment including significant C sequestration in post-agrogenic ecosystems. The extra C sink in NEP of post-agrogenic ecosystems on Russia (45.5 Mha) and Kazakhstan (12.9 Mha) during first 20 yrs after LUC was estimated to be 106 ± 26 Mt C yr^{-1} and 18.9 Mt C yr^{-1}, respectively. The average rate of soil C sequestration in the upper 0–20 cm layer for the same period accounted for 60.8 ± 5.6 Mt C per year in both countries. According to our estimations, the organic C stock in the former arable layer has increased by nearly 5% of total C stocks in upper 0–20 cm layer of arable soils during first 20 yrs of post-agrogenic evolution. Moreover, the soil C build-up due to natural vegetation establishment occurs much slower than SOC losses after converting of grassland or forest to arable land. It should be considered in future if a new idle land expansion might start.

Currently, principal part of the former USSR acts as an absolute sink of atmospheric CO_2. The spontaneous withdrawal of croplands in the early 1990s provided an additional C sink that could annually compensate about 36 and 49% of the current fossil fuel emissions in Russia and Kazakhstan, respectively. We consider that the assessments presented in this study may considerably contribute to the Kyoto implementation policies since they clearly describe C accumulation processes in soils of Russia and Kazakhstan caused by economic crisis in the end of last century. Hence, we conclude that the USSR disintegration and following collapse of collective farming system in the early 1990s provide positive prolonged ecological implications including strong effects on C cycle and budget.

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References

Barford, C.C., Wofsy, S.C., Goulden, M.L., Munger, J.W., Pyle, E.H., Urbanski, S.P., Hutyra, L., Saleska, S.R., Fitzjarrald, D., Moore, K., 2001. Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. Science 294, 1688–1691.
Bazilevich, N.I., 1993. Biological Productivity of Ecosystems in Northern Eurasia (Biologicheskaya productivnost'ecosistem Severnoi Evrazii). Nauka, Moscow (in Russian).
Belelli Marchesini, L., Papale, D., Reichstein, M., et al., 2007. Carbon balance assessment of a natural steppe of southern Siberia by multiple constraint approach. Biogeosci. Discuss. 4, 165–208.
Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., Marland, G., 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. PNAS 104 (47), 18866–18870.
Dolman, A.J., Shvidenko, A., Schepaschenko, D., Ciais, P., Tchebakova, N., Chen, T., van der Molen, M.K., Belelli Marchesini, L., Maximov, T.C., Maksyutov, S., Schulze, E.D., 2012. An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion methods. Biogeosciences 9, 5323–5340.
Fridland, V.M., 1988. Soil Map of the Russian Soviet Federative Socialist Republic at Scale 1:2.5 M. (All Union Academy of Agricultural Sciences, Government Administration on Geodesy and Cartography (GUGK), USSR) (in Russian).
Gulbe, A.Y., 2009. Dynamics of phytomass and annual productivity of birch forest on abandoned land in southern taiga sub-zone. In: Romanovsky, M.G. (Ed.), Production Process and Structure of Forest Biogeocoenosis: Theory and Experiment, pp. 229–243 (Moscow. (in Russian)).
Guo, L.B., Gifford, R.M., 2002. Soil carbon stock and land use change: a meta analysis. Glob. Chang. Biol. 8, 345–360.
Henebry, G.M., 2009. Carbon in idle croplands. Nature 457 (26), 1089–1090.
Hooker, T.D., Compton, J.E., 2003. Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. Ecol. Appl. 13, 299–313.
Houghton, R.A., 2010. How well do we know the flux of CO_2 from land-use change? Tellus 62B, 337–351.
Houghton, R.A., Goodale, C.L., 2004. Effects of land-use change on the carbon balance of terrestrial ecosystems. Ecosystems and Land Use Change. Geophysical Monograph Series 153, pp. 85–98.
IPCC, 2000. Land use, land-use change and forestry (LULUCF). Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK.
IPCC, 2013. Fifth Assessment Report: Climate Change (AR5) Land Use, Land-Use Change and Forestry. http://www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=93.
Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manag. 140, 227–238.
Kalinina, O., Goryachkin, S.V., Karavaeva, N.A., et al., 2010. Dynamics of carbon pools in post-agrogenic sandy soils of southern taiga of Russia. Carbon Balance Manage. 5, 1 (available from http://www.cbmjournal.com/content/5/1/1).
Kalinina, O., Krause, S.E., Goryachkin, S.V., et al., 2011. Self-restoration of post-agrogenic chernozems of Russia: soil development, carbon stocks, and dynamics of carbon pools. Geoderma 162, 196–206.
Kalinina, O., Chertov, O., Dolgikh, A.V., et al., 2013. Self-restoration of post-agrogenic Stagnic Albeluvisols: soil development, carbon stocks and dynamics of carbon pools. Geoderma 207–208, 221–233.
Kalinina, O., Goryachkin, S.V., Lyuri, D.I., Giani, L., 2015. Post-agrogenic development of vegetation, soils, and carbon stocks under self-restoration in different climatic zones of European Russia. Catena 129, 18–29.
Kurganova, I., Kudeayrov, V., 2012. Ecosystems of Russia and global carbon budget. Sci. Russ. 5 (191), 25–33.
Kurganova, I.N., Lopes de Gerenyu, V.O., 2008. Assessment of changes in soil organic carbon storage in soils of Russia, 1990–2020. Eurasian Soil Sci. 41 (13), 1371–1377.
Kurganova, I.N., Lopes de Gerenyu, V.O., 2009. The stock of organic carbon in soils of the Russian Federation: updated estimation in connection with land use changes. Dokl. Biol. Sci. 426, 219–221.

Kurganova, I., Yermolaev, A., Lopes de Gerenyu, V., Larionova, A., Kuzyakov, Y., Keller, T., Lange, S., 2007. Carbon balance in soils of abandoned lands in Moscow region. Eurasian Soil Sci. 40 (1), 50–58.

Kurganova, I.N., Lopes de Gerenyu, V.O., Myakshina, T.N., Sapronov, D.V., Lichko, V.I., Yermolaev, A.M., 2008. Changes in the carbon stocks of former croplands in Russia. Žemės Ūko Mokslai 15 (4), 10–15.

Kurganova, I.N., Kudeyarov, V.N., Lopes De Gerenyu, V.O., 2010a. Updated estimate of carbon balance on Russian Territory. Tellus 62 (B), 497–505.

Kurganova, I.N., Lopes de Gerenyu, V.O., Shvidenko, A.Z., Sapozhnikov, P.M., 2010b. Changes in the organic carbon pool of abandoned soils in Russia (1990–2004). Eurasian Soil Sci. 43, 333–340.

Kurganova, I., Lopes de Gerenyu, V., Six, J., Kuzyakov, Y., 2014. Carbon cost of collective farming collapse in Russia. Glob. Chang. Biol. 20 (3), 938–947.

Larionova, A.A., Yevdokimov, I.V., Kurganova, I.N., Sapronov, D.V., Kuznetsova, L.G., Lopes de Gerenyu, V.O., 2003a. Root respiration and its contribution to the CO_2 emission from soil. Eurasian Soil Sci. 2, 173–184.

Larionova, A.A., Rozonova, L.N., Yevdokimov, I.V., Yermolayev, A.M., Kurganova, I.N., Blagodatsky, S.A., 2003b. Land-use change and management effects on carbon sequestration in soils of Russia's South Taiga zone. Tellus 55B, 331–337.

Lyuri, D.I., Goryachkin, S.V., Karavaeva, N.A., Denisenko, E.A., Nafedova, T.G., 2010. Dynamics of Agricultural Lands of Russia in XX Century and Postagrogenic Restoration of Vegetation and Soils. Geos, Moscow, p. 416 (in Russian).

Lyuri, D.I., Karelin, D.V., Kudikov, A.V., Goryachkin, S.V., 2013. Changes in soil respiration in the course of the postagrogenic succession on sandy soils in the southern taiga zone. Eurasian Soil Sci. 46 (9), 935–947.

Morgounov, A., Trethowan, R., 2008. Avenues to increase yield potential of short season, high latitude wheat in northern Kazakhstan and Siberia. In: Reynolds, M.P., Pietragalla, J., Braun, H.-J. (Eds.), International Symposium on Wheat Yield Potential: Challenges to International Wheat Breeding. CIMMYT, Mexico, D.F., pp. 161–166.

Nilsson, S., Shvidenko, A., Stolbovoi, V., Gluck, M., Jonas, M., Obersteiner, M., 2000. Full carbon account for Russia: Interim Report IR-00-021. IIASA, Laxenburg, Austria, p. 180 (available: http://www.iiasa.ac.at).

Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 19, 988–993.

Pérez-Cruzado, C., Mansilla-Salinero, P., Rodríguez-Soalleiro, R., Merino, A., 2011. Influence of tree species on carbon sequestration in afforested pastures in a humid temperate region. Plant Soil 11, 333–353.

Perez-Quezada, J.F., Saliendra, N.Z., Akshalov, K., Johnson, D.A., Laca, E.A., 2010. Land use influences carbon fluxes in northern Kazakhstan. Rangel. Ecol. Manag. 63, 82–93.

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., van Wesemael, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone — carbon response functions as a model approach. Glob. Chang. Biol. 17, 2415–2427.

Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Chang. Biol. 6, 317–327.

Potter, K.N., Torbert, H.A., Johnson, H.B., Tischler, C.R., 2000. Carbon storage after long-term grass establishment on degraded soils. Soil Sci. 164, 718–725.

Rojkov, V.A., Wagner, V.B., Kogut, B.M., Konyushkov, D.E., Nilsson, S., Sheremet, V.B., Shvidenko, A.Z., 1996. Soil carbon estimates and soil carbon map for Russia. Working Paper. IIASA, Laxenburg, Austria, p. 44 (available from http://www.iiasa.ac.at).

Romanovskaya, A.A., 2008. Carbon and nitrogen accumulation in abandoned lands of Russia. Lžūu Mokslo Darbai 80 (33), 82–91 (in Russian).

Russia in figures, 2012. Rosstat, Moscow available from, http://www.gks.ru/bgd/regl/b12_12/IssWWW.exe/Stg/d01/15-12.htm (Accessed on 4 December 20012).

Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A.V., Kuemmerle, T., Balmann, A., 2013. Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine and Belarus Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. Glob. Biogeochem. Cycles 27, 1175–1185.

Schlesinger, W.H., 1986. Changes in soil carbon storage and associated properties with disturbance and recovery. In: Trabalka, J.R., Reichle, D.E. (Eds.), The Changing Carbon Cycle: A Global Analysis. Springer-Verlag, New York, pp. 194–220.

Shvidenko, A., Nilsson, S., 2003. A synthesis of the impact of Russian forests on the global carbon budget for 1961–1998. Tellus B55, 391–415.

Shvidenko, A., Schepaschenko, D., Vaganov, E., Sukhinin, A., Mc-Callum, I., Maksyutov, S., Lakyda, I., 2011. Impacts of vegetation fire in Russian territories on ecosystems and global carbon budget in 1998–2010. Dokl. Earth Sci. 441, 1678–1682.

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. 8, 394–407.

Soussana, J.-F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., Arrouays, D., 2004. Carbon cycling and sequestration opportunities in temperate grasslands. Soil Use Manag. 20, 219–230.

Uhl, C., Buschbacher, R., Serrao, E.A.S., 1988. Abandoned pastures in eastern Amazonia. I. Patterns of plant succession. J. Ecol. 76, 663–681.

Vuichard, N., Ciais, P., Belelli Marchesini, L., Smith, P., Valentini, R., 2008. Carbon sequestration due to the abandonment of agriculture in the former USSR since 1990. Glob. Biogeochem. Cycles 22, GB4018. http://dx.doi.org/10.1029/2008GB003212.

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. 66, 1930–1946.

World reference base for soil resources, 2014. International Soil Classification System For Naming Soils and Creating Legends for Soil Maps. FAO, Rome.

Zamolodchikov, D.G., Grabovskii, V.I., Kraev, G.N., 2011. Twenty years retrospective forest carbon dynamics in Russia. Contemp. Probl. Ecol. 4, 706–715 (http://www.iea.org/).