Catena 133 (2015) 461–466

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

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

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ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form 1 June 2015
Accepted 4 June 2015
Available online 18 June 2015

Keywords:
Land use change
Soil carbon stocks
Net ecosystem production
Post-agrogenic evolution
Greenhouse effect mitigation
Former USSR

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 (ΔSOC) 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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http://dx.doi.org/10.1016/j.catena.2015.06.002
0341-8162/

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).