

Land-use change and management effects on carbon sequestration in soils of Russia's South Taiga zone

By A. A. LARIONOVA*, L. N. ROZANOVA, I. V. YEVDOKIMOV, A. M. YERMOLAYEV, I. N. KURGANOVA and S. A. BLAGODATSKY, *Institute of Physico-Chemical and Biological Problems in Soil Science, Pushchino, Moscow Region 142290, Russia*

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ABSTRACT

The impact of land use change and management on soil C sequestration was investigated during the 1980s–1990s on gray forest soils in Pushchino, and on the soddy-podzolic soil in Prioksko-Terrasny Biosphere Reserve, Moscow Region, Russia (54°50'N, 37°35'E). Mean annual rates of C sequestration after establishment of perennials (layer 0–60 cm) were 63–182 g C m⁻² and 22–43 g C m⁻² for gray forest and soddy-podzolic soils, respectively. Grassing resulted in higher soil C accumulation than afforestation. Cutting and application of NPK fertilisers increased soil C accumulation, but newly formed soil organic matter was less resistant to decomposition than in unfertilised soil. Preliminary calculations of C sequestration due to abandonment of arable land in Russia since the early 1990s suggest that total C accumulation in soil and the plant biomass could represent about one tenth of industrial CO₂ emissions.

1. Introduction

The net CO₂ flux between terrestrial ecosystems and the atmosphere is determined by the ratio between the rates of two global processes, CO₂ emission caused by respiration of soil heterotrophic microorganisms and animals decomposing litter, and a CO₂ sink as net primary production (NPP) of plants.

The sequestration of CO₂ in ecosystems leads to reduction in emissions. However, the allocation of sequestered carbon is very important: assimilation in NPP is considered as a temporary stock, while C accumulation in such a stable pool as soil organic matter (SOM) is preferable. In turn, soil C is divided into pools with different resistance to decomposition: (i) a light fraction, which includes easily decomposable organic substances such as plant detritus and products of their initial decomposition, microbial biomass and microbial metabolites; (ii) stable humus, which is plant organic material resistant to decomposition and humic

substances protected by clay minerals. As C sequestration in stable humus is the most effective mitigation option, an assessment of both the rate of SOM accumulation and the decomposability of newly formed organic matter is urgently needed. The intention of the Kyoto Protocol is to encourage activities that reduce CO₂ emissions to the atmosphere. As sequestration in stable forms of organic matter can contribute to reduction in emissions, information on how agricultural practices influence the C balance is urgently needed.

Land management practices that are shown to increase C sequestration in terrestrial ecosystems include improved management of cropland by no tillage and application of organic fertiliser. Changes in land use caused by afforestation and grassing of arable land can also increase C storage. Regeneration of perennial vegetation may be more effective in sequestering C than the improved management of arable soils (Paustian et al., 1997; Smith et al., 2000). However, rates of soil C sequestration can vary greatly for different forest and grassland sites (Post and Kwon, 2000). C accumulation in soil depends on regional features, such as the duration of perennial regrowth and the

*Corresponding author.
e-mail: iyevd@issp.psn.ru, ilyaevd@yahoo.com

extent of soil degradation before forest or grassland establishment (Kirillova, 1999).

Since the early 1990s about one fourth of the arable soil area of Russia has been abandoned because of economic depression. During 1990–1995 the area of agricultural land decreased by 34×10^6 ha (Pankova and Novikova, 2000). At the same time land degraded by wind and water erosion, soil acidification and salinisation also decreased. These degraded soils were abandoned first. The area of degraded agricultural land in Russia due to wind and water erosion for 1990 was 21.5×10^6 and 41.5×10^6 ha, respectively (Pankova and Novikova, 2000). In 1995 the area of eroded soils had decreased by 5.8×10^6 ha. Hence, the remaining area of degraded soils represents a significant potential C sink if converted to native vegetation.

There are few quantitative estimates of the C balance in such ecosystems and rates of humus accumulation in soil, despite their potential importance in mitigating the negative consequences of greenhouse effect.

Here, the aim of our work was to estimate: (i) the C balance of ecosystems and soils under agricultural use; (ii) the accumulation of C when degraded arable soils are sown into meadow or reforested.

2. Materials and methods

2.1. Field experiment

The investigations were carried out in the 1980s–1990s on gray forest soils (C_{org} 1.0–2.4%, pH 5.6–6.5) in Pushchino, and on soddy-podzolic soils (C_{org} 0.9–1.5%, pH 5.0–5.6) in Prioksko-Terrasny Biosphere Reserve, Moscow Region, Russia (54°50'N, 37°35'E). The arable soils studied have been intensively used for agriculture for over 250 yr.

At the grassland site on gray forest soils a mixture of *Festuca pratensis* (Huds.), *Phleum pratense* (L.) and *Trifolium pratense* (L.) was sown in 1980. Bunch, loose-tussock and quitch grasses currently predominate in the sward. Two factors, hay cutting and NPK fertilisation at a rate of 60 kg ha^{-1} , were tested. Three treatments were investigated: unfertilised uncut, unfertilised cut and fertilised cut. The grassland site on the soddy-podzolic soil was unfertilised cut meadow 47 yr after abandonment of arable use.

The forest site on gray forest soils was a secondary mixed aspen–lime–birch forest rich in herbs, with a mean tree age of 40–50 yr; this site has been under forest for about 100 yr. The forest plots on soddy-podzolic

soils are mature mixed pine–lime–aspen–oak forest with tree ages up to 100 yr, and secondary birch forest 47 yr after abandonment of arable use, with mean tree age of 20–30 yr.

2.2. Determination of carbon balance in soil

The balance of SOM during grassing and afforestation of arable soils was calculated as the difference between C storage in arable soil before perennial establishment and in forest or grassland soil. C storage in soils, equal to SOM content multiplied by the soil bulk density, was determined to a depth of 60 cm. The organic carbon in soil (C_{org}) was estimated by the dichromate oxidation procedure (Orlov and Grishina, 1981). To calculate CO_2 emissions caused by production and application of N fertiliser we used an emission factor of 1.4 mol CO_2 per mol N applied as inorganic fertiliser (Schlesinger, 2000).

2.3. Incubation experiments with soils

Arable gray forest soil was sampled after 18 yr of grassing from the plots in October, 1999 from 0–20 cm depth. Root-free soil samples (100 g) were adjusted to 70% of water-holding capacity and incubated over 6 months at 22 °C, until the difference in soil respiration between grassland treatments was not significant. Carbon immobilised in microbial biomass (C_{mic}) was determined before and after incubation by the rehydration–extraction procedure (Blagodatsky and Yevdokimov, 1998). All the results of soil analysis are expressed on an oven-dry basis.

3. Results and Discussion

3.1. Carbon accumulation in arable soil after grassing and afforestation

C balance in arable soils was close to zero, without statistically significant changes in SOM content during the experiment (Table 1). Previous estimates of C balance by difference between NPP and CO_2 emissions from the gray forest soil (Larionova et al., 1998) evidence the equilibration of these fluxes in most unfertilised crops. Many of the old agricultural soils in Russia have reached steady-state conditions, i.e. losses of humus have markedly declined and soil C has now stabilised at values lower than the initial level (Orlov et al., 1996).

Table 1. Carbon accumulation in soil ($\pm SE$)

Ecosystem	Treatment	C _{org} , kg m ⁻²		Accumulation, gC m ⁻² yr ⁻¹	
		0–20 cm	0–60 cm	0–20cm	0–60 cm
		Gray forest soil			
18 yr grassland	Uncut unfertilised	3.32 ± 0.03	6.65 ± 0.29	73	161
	Cut unfertilised	3.49 ± 0.05	6.16 ± 0.28	83	142
	Cut fertilised	3.67 ± 0.09	7.04 ± 0.15	85 ^a	174 ^a
Moderately eroded arable land before grassland establishment		2.18 ± 0.08	3.76 ± 0.10	ND ^b	ND
100 yr forest	Cut unfertilised	6.84 ± 0.16	11.16 ± 0.18	39	63
Non-eroded arable land	Unfertilised	2.77 ± 0.09	6.03 ± 0.11	0	0
		Soddy–podzolic soil			
47 yr grassland	Cut unfertilised	3.87 ± 0.21	5.18 ± 0.22	39	43
47 yr forest	Uncut unfertilised	2.54 ± 0.11	4.20 ± 0.12	11	22
Mature forest	Unfertilised uncut	3.80 ± 0.15	5.09 ± 0.20	ND	ND
Arable land	Unfertilised	2.05 ± 0.09	3.15 ± 0.10	0	0

^aTaking into account 8 g C m⁻² yr⁻¹ CO₂ emissions by the use of N fertilisers.

^bND, not determined.

Substantial accumulation of SOM occurred after grassing and afforestation (Table 1). High rates of C accumulation were observed after grassing of gray forest soil. Cutting with fertilisation intensified C accumulation in the grassland soil, although part of the NPP was removed by hay mowing. Among the grassland treatments highest losses of CO₂ and C_{mic} were observed in the cut fertilised variant in 6 mo incubation of gray forest soil (Table 2). Hence, cut fertilized grassland showed the highest rate of C accumulation in SOM during grassland establishment and the highest rate of SOM decomposition during soil incubation. This indicated that the newly formed SOM was highly decomposable. High decomposability of newly formed SOM should be taken into account when this treatment is applied.

Cutting with fertilisation is commonly recommended for conversion of arable land to permanent grassland. If managed grassland after soil improvement is to be converted back to arable land, a large proportion of the accumulated C is expected to be rapidly lost. The CO₂ emissions of 8.4 g C m⁻² yr⁻¹ from fossil-fuel use to produce and transport the fertilisers significantly decreased the positive effect of NPK application and resulted in equal C accumulation in topsoil of fertilised and unfertilised cut grasslands. Thus, abandonment of arable land without fertilising and cutting, or cutting without fertiliser application, is recommended for improvement of the soil. The cut

unfertilised treatment caused higher SOM accumulation in topsoil than the uncut unfertilised treatment, while the opposite effect occurred in deeper soil layers (Table 1). Cutting is known to stimulate root growth and thus to increase annual belowground NPP and SOM accumulation in topsoil (Titlyanova et al., 1996). Thus, introducing grass species with deep roots into the plant community would probably remove the need for improvements in the C balance of soils under grasslands by NPK fertilisation.

Compared to grassing, afforestation resulted in lower rates of SOM accumulation on gray forest soil (Table 1). The reason is the different ages of ecosystems. The maximum rate of SOM accumulation occurred within 20–30 yr after establishment of perennials. During this time, NPP had stabilised at a high level, by not a high intensity of heterotrophic respiration (Titlyanova and Tesarova, 1991). The respiration of heterotrophs in "young" ecosystems comprises approximately half of NPP. In mature ecosystems C accumulation decreases due to enhanced heterotrophic respiration (up to 95–100% of NPP). We have previously reported (Larionova et al., 1998) that respiration of heterotrophs in cut unfertilised grassland is approximately equal to 50% of NPP, compared to forest soils where as much as 80% NPP is respired by heterotrophs. Hence, maximal rates of C accumulation occurred in the grassland soil, while in the forest soil C storage had stabilised. The enhanced

Table 2. *Microbial biomass and respiration of gray forest soil ($\pm SE$)*

Ecosystem	Treatment	C_{mic} , g C/100 g soil (0–20 cm)	C_{mic}/C_{org} , % (0–20 cm)	CO ₂ losses for 6 mo incubation, mg CO ₂ -C per 100 g soil	C_{mic} decrease after 6 mo. incubation (mg C per 100 g soil)
18-yr grassland	Uncut unfertilised	61.0 $\pm$ 1.1	4.4 $\pm$ 0.2	176.5 $\pm$ 4.2	14.7 $\pm$ 3.6
	Cut unfertilised	82.2 $\pm$ 2.6	6.0 $\pm$ 0.1	220.8 $\pm$ 1.8	25.6 $\pm$ 7.1
	Cut unfertilised	80.4 $\pm$ 2.3	5.7 $\pm$ 0.1	247.6 $\pm$ 2.1	37.7 $\pm$ 6.0
100 yr forest	Cut unfertilised	130.5 $\pm$ 5.8	6.7 $\pm$ 0.2	449.8 $\pm$ 2.3	8.1 $\pm$ 3.5
Non-eroded arable soil	Unfertilised	35.8 $\pm$ 1.1	3.7 $\pm$ 0.2	39.6 $\pm$ 0.1	8.4 $\pm$ 1.5

activity of heterotrophs at the forest site is reflected in the data for microbial respiration, microbial biomass and C_{mic}/C_{org} ratio in the soil (Table 2). Both C_{mic} and C_{mic}/C_{org} values were higher in the forest than in the grassland soil. CO₂ emissions were also highest in the forest soil during 6 mo incubation (Table 2).

Direct comparison of the effect of grassing and afforestation on SOM accumulation was possible for the soddy-podzolic soil, because both grassland and forest had been established 47 yr earlier. The grassland soil accumulated twice as much C as the soil under forest (0–60 cm) (Table 1). However, Post and Kwon (2000) reported that rates of SOM accumulation did not differ between afforestation and grassing. This is supported by the absence of a significant difference between C_{org} content in soil under different native ecosystems on the same soil type (Orlov et al., 1996; Kononova, 1984). The difference we observed in C sequestration for grassing and afforestation on soddy-podzolic soil is explained by higher rates of growth and turnover of grasses compared to the slower-growing and less decomposable woody plants. This difference seems to disappear over time. C_{org} content and SOM storage in grassland soddy-podzolic soils are about the same as in the mature forest site (Table 1). In contrast, SOM storage after 47 yr afforestation was much lower. Hence, grassing of arable soil results in more rapid SOM accumulation soon after establishment, while under afforestation, SOM accumulation occurs more slowly.

3.2. Carbon accumulation in soddy-podzolic and gray forest soil

The data on SOM accumulation showed that C sequestration in soddy-podzolic was more than two-fold slower than in gray forest soil. These differences may be explained by the age of the grassland or the forest, and by the soil type. The higher C accumulation in the 18 yr grassland on gray forest soil compared to 47 yr

grassland on soddy-podzolic soil can be explained by ecosystem age (Table 1). In the forests the opposite trend was observed: C sequestration in the gray forest soil under 100 yr old forest was three times higher than in soddy-podzolic soil under 47 yr old forest. This difference in C accumulation can be explained by soil type, and in particular by differences in clay content and distribution in the soils studied. In sandy soddy-podzolic soils only the upper 15 cm layer is comprised of loamy sand, with deeper sand horizons being free of clay, while all the horizons of the gray forest soil tested have a silt loam texture. The formation of recalcitrant complexes between clay minerals and organic compounds can protect SOM from decomposition (Christensen, 1992). Therefore, SOM accumulation partly depends on clay content: the substantial accumulation of SOM in the soddy-podzolic soil was observed in the topsoil, while in the gray forest soil only 40–60% SOM accumulated in upper 0–20 cm layer (Table 1). Hence, the low C accumulation rate is a feature of sandy soddy-podzolic soil.

Comparison of C sequestration in the soils studied with the global mean value calculated by Post and Kwon (2000) showed that C sequestration in the gray forest soil was much higher, while that in soddy-podzolic soil was approximately the same as for the world-wide mean value (Table 3). The majority of data in Post and Kwon's (2000) review was for SOM accumulation in topsoils only. The high rates of SOM accumulation in the gray forest soil in our study are explained by the fact that accumulation occurs in both the top and deeper soil horizons (Table 1).

Another reason for the high SOM accumulation rate in the gray forest soil studied was the intensive humus depletion due to soil erosion before the grassland was established. Carbon stored in the eroded arable soil before grassing was much lower than that in non-eroded arable land, especially when the 0–60 cm layers are compared (Table 1). Similar results were reported by Kirillova, 1999 (Table 3).

Table 3. Rates of C accumulation in soil during grassland establishment (Russia and other countries), ($\text{g C m}^{-2} \text{ yr}^{-1}$)

Land-use change	Years of grassing	Soil type	Soil depth, cm	Rate of C accumulation	Reference
Sown grassland on arable land	18	Gray forest soil	60	161	This study
Grassland regrowth on abandoned arable land	47	Soddy-podzolic soil	60	43	This study
Sown grassland on eroded arable land	15	Gray forest soil	20	129	Kyrillova, 1999
Sown grassland on non-eroded arable land	15	Gray forest soil	20	47	Kyrillova, 1999
Pasture abandoned to uncut grassland	14	Chernozem	20	128	Afanasyev and Rotova, 1986
Grassland on coal mine spoil	25	Mine tailing (parent material)	5	98	Titlyanova and Tesarova, 1991
Grassland regrowth on coal mine spoil	30	Mine tailing (parent material)	5	135	Yeterevskaya et al., 1985
Cropland or forest conversion to grassland	6–81	World-wide variety of soils	5–300	33	Post and Kwon, 2000

3.3. Preliminary estimates of carbon accumulations in abandoned arable soils of Russia

To assess the C sequestration in abandoned arable soils of Russia, we used both the results of our investigations and the data obtained by other authors (Table 3). The data presented in Table 3 summarise C accumulation rates in chernosems and gray forest soils including mining spoils which are located on the territory occupied by these two soil types. Gray forest soils and chernozems are characterised by high productivity in both European Russia and Siberia. The share of these soils in the total arable area of Russia comprises about 50%. Up to 95% of chernozems and 80% of gray forest soils are used in agriculture; about 40% of area occupied by two soil types are degraded due to wind and water erosion (Dobrovolsky and Uru-sevskaya, 1984). The share of sandy soddy-podzolic soils in the total arable area of Russia does not exceed 1–2%. Taking into account the small area occupied by sandy soddy-podzolic soils, the mean C accumulation in Russian soils due to agriculture abandonment is about $130 \text{ g C m}^{-2} \text{ yr}^{-1}$. If this accumulation is applied to the $34 \times 10^6 \text{ ha}$ of abandoned arable land in Russia (Pankova and Novikova, 2000), total C accumulation comprises 44 Tg yr^{-1} . As total CO_2 emissions for Russia due to industrial processes were 676 Tg yr^{-1} in 1990 (Nilsson et al., 2000), C sequestration by abandonment of agricultural land comprises

approximately 6.5% of industrial CO_2 emission. This value is to be doubled if we consider the capture of CO_2 from the atmosphere due to agricultural abandonment both in SOM and in plants. The doubling arises from the following general suggestion. During the first 7–8 yr of perennial regrowth accumulation of SOM comprises about 25–30% of C sequestration in the ecosystem (Titlyanova and Tesarova, 1991). The rest of the sequestered carbon is stored in living roots and dead plant parts (litter and dead roots). The amount of living roots in sown grasslands is five times greater than in crops and the storage of plant residues as surface litter, detritus and dead roots exceeds the mass of plant residues in agricultural ecosystems by about 20 times (Yermolayev and Shirshova, 2000). In two decades of agriculture abandonment annual accumulation in SOM approximates C sequestration in the grassland ecosystem. The new acceleration of C sequestration in the ecosystem probably corresponds to the time of substitution of grasses by woody plants.

To obtain more accurate assessments, more precise information is needed for the abandoned agricultural land of Russia, as existing maps of land use (Nilsson et al., 2000) do not reflect recent land abandonment. Investigations of C accumulation in long-term experiments involving the re-establishment of native vegetation are also needed. The variability of mean rates of C sequestration depends on inter-annual variations in SOM dynamics after agriculture abandonment.

Annual SOM accumulation in the top 10 cm of the gray forest soil studied during 16 yr grassland establishment varied from -300 to $+470 \text{ g C m}^{-2}\text{yr}^{-1}$ (Yermolayev and Shirshova, 2000). Long-term trends and irregular fluctuations in SOM accumulation affect the magnitude of mean C sequestration by soil. The separation of these trends and fluctuations of SOM dynamics would be possible only in long-term investigations of SOM accumulation in grassing experiments. Studies of the C sequestration potential for the wide range of Russian soils are needed with special attention being given to the relationships between SOM accumulation rates and soil properties such as clay content, cation-exchange capacity or depth of soil profile.

The new information about C accumulation in clay soddy-podzolic and chestnut soils for the first 10–20 yr of abandonment of agriculture will significantly improve these estimates. The share of arable soddy-podzolic and chestnut soils comprise 13 and 7%, respectively, of the total arable area of Russia (Dobrovolsky and Urusevskaya, 1984). Thus, reducing the area of arable soils and re-establishing perennial grasses is an important process for mitigating industrial CO_2 emissions. Our assessments show that 13% of fossil fuel emissions can be sequestered by agriculture abandonment. Or, roughly (taking into account that the suggestions made are not exact enough), at least one tenth of CO_2 emissions from fossil fuel combustion is sequestered in abandoned croplands on the Russian territory. This sink of CO_2 is rather weak compared to proposed C sequestration in woody plants by substitution of old forests by young plantations and afforestation of marginal lands, which is about one third of industrial emissions of Russia (Isaev et al., 1995). However, C accumulation due to agriculture abandonment is a significant part of C balance not included into calcu-

lations of the Full Carbon Account of Russia (Nilsson et al., 2000).

4. Conclusion

Grassing and afforestation of degraded arable lands resulted in significant accumulation of SOM. Accumulation rates in clay gray forest soils were much higher than those in sandy soddy-podzolic soils. The establishment of perennial grassland over 47 yr doubled the SOM accumulation rate compared to the effect of afforestation for the same period.

Maximum SOM accumulation rates were observed in cut, fertilized grassland on gray forest soil. The newly formed humus in fertilised soil was more readily decomposable than that in unfertilised soil. We therefore recommend cutting and fertilisation when converting arable land to permanent grassland. However, if managed grassland is converted to arable land again, neither cutting nor fertiliser application is recommended.

Preliminary calculations of C sequestration in abandoned land could offset approximately one tenth of the industrial CO_2 emissions from Russia (both C sequestration in NPP and in soil are included in this calculation). Accordingly, C sequestration in abandoned land should be included in calculations of the national C budget of Russia.

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