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Carbon balance in arable grey forest soils

ABSTRACT. Land use management strategies have been developed to decrease the emissions of greenhouse gases to the atmosphere and to increase C stock in stable forms of soil humus. The impact of land use change and management on soil C sequestration was studied in the years 1980–1990 on grey forest soils in Pushchino, Moscow Region, Russia (54°50' N, 37°35' E). At present, up to 80% of grey forest soils (Humic Luvisols) are used for agriculture; these soils have been intensively used for crop production since the beginning of 19 th century. Estimates of carbon sink as net primary production and source as CO_2 emission evidence the equilibration of these fluxes in most nonfertilised crops. Application of mineral fertilisers separately and in combination with low rates of organic fertilisers promoted the establishment of a mostly positive C balance in the agroecosystems studied. However, the inclusions of crops with negative C balance in crop rotations (fallow and spring cereals) led to the slow increase in stable forms, i.e. in soil humus.

KEY WORDS: soil respiration, C balance, cropland, fertiliser application, C sequestration

The net CO_2 flux between terrestrial ecosystems and the atmosphere is determined by the ratio between the rates of two global processes – CO_2 emission caused by respiration of soil heterotrophic microorganisms and animals decomposing litter, and CO_2 sink as net primary production (NPP) of plants.

The C balance of natural (undisturbed) ecosystems is typically positive or close to zero. Agricultural ecosystems are usually considered as a major source of CO_2 and other greenhouse gases since management effects can increase the

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mineralisation of the soil organic matter [Schlesinger 1985; Houghton, Skole 1990; Bouwman 1990; Guo, Gifford 2002].

The largest CO_2 emissions disturbance of the C balance is often observed after the initial cultivation of natural ecosystems, which results in large decreases in standing stock of C and soil C content [Davidson, Ackermann 1993; Orlov et al. 1996; Paustian et al. 1997; Titlyanova, Tesarova 1991]. Estimates of CO_2 emissions from the territory of Russia [Kobak 1988; Kurganova, Kudeyarov 1998; Nilsson et al. 2000] suggest higher emissions from arable soils than from soils in native ecosystems. These estimates are uncertain because 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; Kogut 1998; Shevtsova, Volodarskaya 1998].

An assessment of the effects of widely used agricultural practices on the C balance of arable soils in Russia is urgently needed to determine their contribution to global CO_2 emissions more precisely. The sequestration of CO_2 in the ecosystems leads to emissions reduction. The intention of the Kyoto Protocol is to encourage activities which reduce CO_2 emissions to the atmosphere. As C sequestration can contribute to emissions reduction, information on how agricultural practices influence the C balance is urgently needed.

The aim of our work was to estimate the C balance of ecosystems and soils under agricultural use.

METHODS

The studies were carried out in the 1980–90's on grey forest soils (Humic Luvisols) (C_{org} 1.0–2.4%, pH 5.6–6.5) Pushchino, Moscow Region, Russia (54°50' N, 37°35' E). The arable soils studied have been intensively used for agriculture since the beginning of 19–th century. At present, up to 80% of grey forest soils are used for crop production.

The cropped site on grey forest soils was 5–year cereal rotation, and it was a part of the field experiment established in the Field Experimental Station of the Institute of Physico–Chemical and Biological Problems in Soil Science. A split–plot design was used. The soil C balance was determined under corn (*Zea mays* L.) in 1984 and 1986, winter wheat (*Triticum aestivum* L.) in 1985–1986 and 1989–1990, spring barley (*Hordeum vulgare* L) in 1985 and 1988, buckwheat (*Fagopyrum esculentum* Moench.) in 1992, and bare fallow in 1993. Three replicate 125 m^2 plots were NPK fertilised at the rates of 90–120 kg/ha. Moderate rates of manure (15–30 t/ha) were applied to maize and winter wheat in 1984–1985, and 5.6 t/ha of cereal straw was added to the soil under winter wheat in 1989–1990.

Nonfertilised controls were also included. The plot with PK fertiliser (N excluded) was used as a control for winter wheat in 1989–1990. Only nonfertilised plots were studied in the agroecosystem with buckwheat and under bare fallow.

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

The C balance in the arable soils was calculated from the difference between the annual C input from NPP, C input with organic fertilisers and C from respiration of heterotrophs (i.e. soil microorganisms) CO_2 losses by application of inorganic N fertilisers were taken into account. C input from NPP was measured by the difference between total NPP and NPP output with harvest. Respiration of heterotrophs was estimated from year–round measurements of CO_2 emissions from the soil, by subtracting the contribution of root respiration to the total CO_2 efflux. The balance equation is as follows:

$$\text{Balance} = \text{NPP} - \text{Harvest} + I_{\text{fert.}} - \text{TSR} + \text{RR} - E_{\text{fert}} \quad (1)$$

where NPP is the sum of aboveground and belowground NPP, $I_{\text{fert.}}$ – C input with organic fertilisers (manure or straw), TSR – total soil respiration measured as CO_2 emissions from the soil surface, RR – respiration of roots, E_{fert} – CO_2 emissions caused by production, transportation and application of N fertiliser. For the calculation of E_{fert} we used an emission factor of 1.4 mol CO_2/1 mol N applied as inorganic fertiliser [Schlesinger 2000].

CO_2 emissions from the soil were measured at 1–2 week intervals during crop growth, daily measurements were carried out during intensive growth of winter wheat in May–July of 1984–1985 and spring barley in May–June of 1988. Monthly measurements of CO_2 emissions were carried out during the cold season from October to April. Carbon dioxide emissions from the soil were measured by CO_2–profile and static chamber methods as described in our previous paper [Larionova et al. 1998]. The root contribution to CO_2 emission was determined under laboratory conditions 4–5 times per growing season at the main growth stages for crops. In corn, wheat and barley the respiration of roots was measured after roots had been removed from soil by a washing procedure. Samples of root–free soil (100 g) and washed roots taken from three cores (from depths of 0–20 cm, and 10 cm diameter) were incubated at 22°C for 1–2 hours, and the increase in CO_2 concentrations, during the incubation was measured. The contribution of buckwheat roots to total soil respiration was estimated by the difference between the respiration of soil with roots and root–free soil [Larionova et al. 1998].

Tab. 1

Grey forest soil from arable and forest sites was sampled from the plots in May, June, August, and October, 1999 from 0–20 cm depth. Root–free soil samples (100 g) were adjusted to 70% of water holding capacity and incubated over 2–6 months at 22°C. Carbon ($C_{mic.}$) immobilised in microbial biomass was determined before and after incubation by the rehydration–extraction procedure [Blagodatsky, Yevdokimov 1998]. All the results of soil analysis are expressed on an oven–dry basis.

CO_2 concentrations in air samples was measured by gas chromatography. The carbon content of plants as the mass fraction of C was measured by CHN–analyser (Carlo Erba, Italy) and was equal to 39–41% and 42–43% in shoots and roots, respectively. The organic carbon in soil ($C_{org.}$) and organic carbon in soil extracts were estimated by the dichromate oxidation procedure. All the results are expressed on an oven–dry basis.

RESULTS

The C inputs from NPP and fertilisers and C losses from respiration of heterotrophs in arable gray forest soil are shown in Table 1. NPP varied from 237 to 1007 g C m^{-2} $year^{-1}$ between the crops studied. The most prominent influence of fertilisation on C input (as NPP) was observed during crop growth. Differences in input from plant debris were less variable (87–208 g C m^{-2} $year^{-1}$) due to the removal of a considerable portion of NPP at harvesting. Low values of C input in spring barley were observed in 1988 due to prolonged soil desiccation in June 1988 during intensive growth of spring cereals. The high values of C input in non-fertilised buckwheat are explained by straw remaining in the field after harvest.

The rates of total soil respiration in the agroecosystems studied were in the range of 0–3.7 g C m^{-2} day^{-1} depending mainly on the sampling date rather than on crops. The annual sums of total soil respiration showed less variability (Tab. 1) and depended mainly on soil moisture and temperature during the growing season. The period of intensive soil CO_2 emission coincided with intensive plant growth, and this occurred at different times for the crops.

The contribution of roots varied from 7 to 89% of total soil respiration between the sampling dates. On an annual basis, the relative contribution of roots depended on the length of the growing season: root respiration comprised 25–30% in spring barley and buckwheat – the crops with short vegetation, and 40–45% in corn and winter wheat – the crops with prolonged growing season.

The annual respiration of heterotrophs differed between the agroecosystems studied from 65 to 185 g C m^{-2} $year^{-1}$. Higher values of the respiration were observed during the years with optimum moisture and temperature conditions over the growing season, while for the years with prolonged desiccation during crops growth lower values were obtained. Respiration of heterotrophs and the input of plant debris to the soil varied depending on fertilisation, with differences between control and fertilised soils not exceeding 25–30%.

The C balance in soil was mostly close to zero or positive. Cultivation of annual crops without fertiliser resulted in zero balance in the soil. Negative balance, i.e. CO_2 source in the atmosphere was observed in spring barley and bare fallow.

Inorganic NPK fertilisation increased C input to the soil with plant residues compared to nonfertilised treatments. Respiration of heterotrophs was slightly decreased or even not changed by NPK application. Estimated release of CO_2 by production and application of inorganic fertilisers (Tab.1) diminished the positive effect of this treatment on C balance, but did not change the balance from positive to negative in the crops studied.

The combination of NPK application with manure and straw addition enhanced both C input and respiration of heterotrophs and it resulted in highly positive C balance in the soil. Despite increased C losses, a positive C balance was established not only due to C input with organic fertiliser, but owing to increased C input from higher NPP as well.

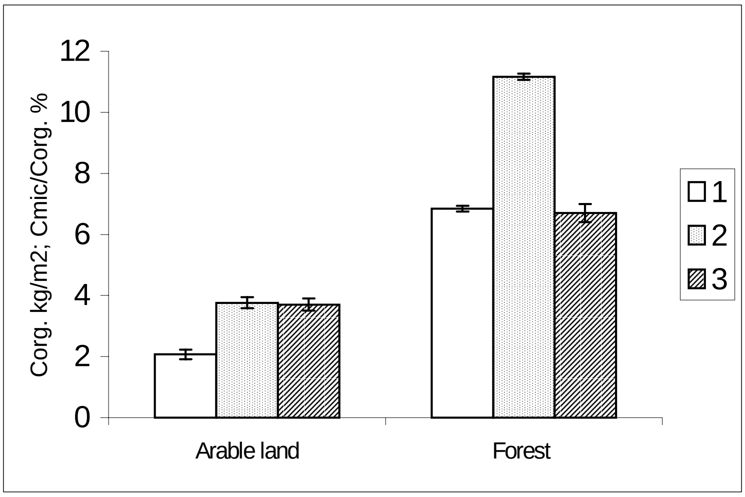

Figure1. SOM storage in surface 0–20 (1) and deep 0–60 (2) soil layers and $C_{mic.}/C_{org.}$ ratio (3) in the soil under forest and cropland. Bars indicate SE

NPK, manure and straw additions in crop rotation did not result in statistically significant increases in SOM and C_{mic} content. C_{org} in arable soil varied from 1.0 to 1.05% while $C_{mic.}$ was 30–53 mg C/100 g soil in all the treatments studied and depended on the sampling date.

SOM content under crops was much lower than in the forest site in both surface and deep soil layers (Fig. 1). C_{mic}/C_{org} ratio reflecting the abundance of microorganisms in SOM was also lower in arable soil. Incubation of grey forest soils sampled in different seasons resulted in a gradual decrease in the CO_2 emission and C_{mic} content with time. Since identical trends were observed, we include only the results of the long–scale experiment with soil sampled in October 1999 (Fig. 2). Six–month incubation of grey forest soil under forest resulted in high CO_2 losses as compared with arable soil, while the decrease in C_{mic} was the same in both forest and arable soils.

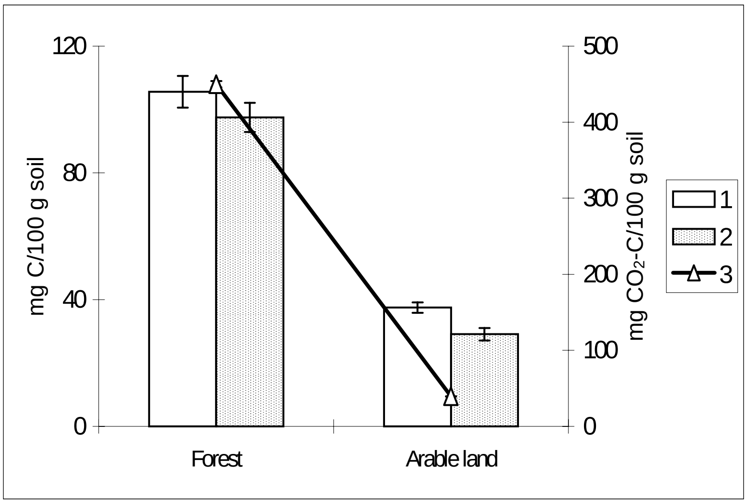

Figure 2. Soil microbial biomass before (1) and after (2) 6–month incubation, and CO_2 losses for the period of 6–month incubation (3). Bars indicate SE

Our results demonstrate that intensively used old arable soils are not in general the principle sources of CO_2 to the atmosphere (Tab. 1).

A comparison of C pools in grey forest soils after afforestation and under crops provides the evidence that the soil under crops represented a strong CO_2 source in the past. The SOM pool in non–eroded arable soil dropped by 2.5 and 1.85 times to the depth of 0–20 cm and 0–60 cm, respectively, compared with the forest soil (Fig. 1). The principal reason for the decrease in soil humus content when natural soils are ploughed is the reduction of litter input to soil [Kononova 1984] and increased SOM mineralisation due to the soil tillage [Paustian et al. 1997]. Besides, natural soils contain a considerable pool of dead organic substances – litter and detritus, i.e. humification proceeds more stably compared with arable soils where the input of plant material takes place only after harvesting.

A decrease in soil humus content in soil as a result of ploughing is known to be the most rapid during the first years of the conversion from a natural ecosystem to the agricultural land. Then losses diminish, and SOM content is stabilised at a new lower level within several decades [Davidson, Ackerman 1993; Orlov et al. 1996]. Low CO_2 and C_{mic} losses during soil incubation (Fig. 2) showed that SOM of cultivated soils was stabilized, and C_{org} content had reached an equilibrium.

Long-term agricultural use causes: i) a decrease in absolute values of both microbial biomass C and the percentage of microbial C in total organic C pool in soil ($C_{mic.}/C_{org.}$) (Fig. 1), ii) depletion of species complex of soil microorganisms [Zelles at al. 1992; Pankhurst et al. 1996], iii) accumulation of substances relatively resistant to decomposition and mineralisation [Orlov 1996]. The three processes listed above are related to the observed decline in humus losses and its stabilisation in arable soils. Losses of humus in old arable soils thus can be reduced to zero when conventional agriculture is applied.

Application of N, P and K significantly increased the input of plant debris to soil but did not change or slightly diminished heterotrophic respiration. Published data support a slight decrease in soil respiration after application of fertilisers [Paustian et al. 1990]. SOM dynamics by N-fertilisation is governed by two main processes: i) increased SOM accumulation owing to higher C input with plant residues in comparison with unfertilised treatment, ii) intensified SOM mineralisation or so–called “priming effect” [Jenkinson 1990; Kuzyakov 2000]. Priming effect is considerable in soils rich in C and N, or soils after addition of easily decomposable organic substances. It rises immediately or very shortly after C– and N–substrate additions [Kuzyakov 2000; Kudeyarov 1999]. Hence, rapid mineralisation of soil organic matter takes place when land is first ploughed rather than for the whole period of long-term agricultural use. Considerable pools of plant debris and detritus remain in soil when natural ecosystems are converted to agricultural land. These C pools are characterised by C/N ratios of 25–150 and decomposed slowly by N deficit in soil [Szegi 1988]. N fertilisation reduces the C/N ratio in soil organic matter and thus increases its rate of decomposition. Stabilisation of humus content in soil mainly occurs as readily decomposable C substrates are depleted. C/N ratios in soil humus are of 15–18 [Orlov et al.1996], i.e. lower than in plant residues. By humus decomposition, addition of mineral N to soil increases the efficiency of C substrate consumption by the soil microbial community. Simultaneously, C input into soil microbial biomass rises, and CO_2 emissions from soil decrease [Blagodatsky et al. 1993]. Consequently, the positive values of C balance were observed due to enhanced NPP input to the soil, while priming effect during SOM decomposition was not detected.

Fertilisation with mineral and organic fertiliser did not affect either C_{org} or C_{mic} when averaged over the growing season, despite C_{mic} being more sensitive to C additions to the soil. No sufficient changes in humus quantity or quality were observed in grey forest soil under study over a 25-year period of NPK fertilisation and regular ploughing of straw into the soil [Nikitishen at al. 1996]. Moreover, accounting of C losses by production and transportation of fertilisers resulted in the evolution of 198 g C m^{-2} to the atmosphere for 25 years of cropping. The absence of SOM accumulation when NPK and organic fertilisers are applied can be explained by the high decomposability of newly formed SOM (and by the inclusion of fallow and spring cereals in the crop rotation (Tab. 1).

Negative C balance was found in spring barley, which has a short growth season (70–80 days), and in bare fallow, when soil was kept free of vegetation cover within the whole growth season.

A strongly negative C balance arose in fallow soil (Tab. 1), with a large increase in NPP of succeeding crops. The large difference in total NPP for winter wheat crops in 1985 and 1990 is attributed to the effect of different previous crops: vetch–oats crops in 1984 and bare fallow in 1989. Fallow cultivation before wheat cropping caused total NPP to double for wheat in the nonfertilised control (Tab. 1). The removal of a large proportion of NPP (grains + straw at harvesting) led to an almost equal C input with NPP as plant debris to soil in 1985 and 1990. Thus, if we compile two years of fallowing and cropping of winter wheat, it would be a negative C balance despite high values of NPP following bare fallow. Frequent soil tillage for weeds suppression (5–6 times per season) intensifies SOM decomposition in bare fallow. Thus, fallowing of fertilised arable soil results in additional acceleration of SOM decomposition. Soil C accumulated during crop growth can be easily lost during the fallow season. Reduced or zero-tillage stabilises SOM accumulated after NPK-fertilisation [Schlesinger 2000]. Hence, fertilisation with reduced tillage, reduction of fallow and spring cereals in the crop rotation, and exclusion of straw removal at harvest is recommended to enhance C sequestration in agroecosystems on grey forest soil.

CONCLUSION

1. Estimates of C balance of grey forest soils in agricultural ecosystems were negative only in spring barley cropping and in fallow soil. Other agricultural ecosystems (winter wheat, corn, buckwheat) did not demonstrate negative C balances, even under conditions of poor agriculture and no fertilisation.

2. Application of mineral fertilisers separately and in combination with organic fertilisers caused an increase in C sequestration in agricultural ecosystems

without sufficient changes in humus content in soil within the first 25 years of crop rotation. A reduction in fallow usage and spring cereals cultivation is recommended to stabilise positive changes in the SOM balance in crop rotation caused by fertilisers application.

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