Soil greenhouse gas emissions and carbon pools in afforested agricultural fields

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Abstract

We studied the development of C pools in ground vegetation, litter, different soil horizons and stand biomass in a chronosequence of 88 afforested sites situated on mineral soil arable land. On afforested organic soil fields we quantified the soil GHG-fluxes with chamber measurements on eight sites. In mineral soil arable lands, the amount of carbon bound in litter increased considerably with increase in afforestation age. In the tilling layer (0-20 cm), the carbon pools decreased with the increase of stand age while those below tilling layer (20-40 cm) remained rather constant. When the carbon bound in tree stands is taken into account afforestation of arable land is a sink of carbon that increases with the time from afforestation. On afforested organic soil fields soil CO_2 fluxes varied from 2100 to 3500 kg CO_2-C ha a^{-1}. The studied organic soil fields acted mainly as small sinks for CH_4 and they all emitted N_2O.

Introduction

Sequestration of atmospheric carbon in soils and biomass has been recognised as an important environmental impact of afforestation. Under Article 3.3 of the Kyoto Protocol, greenhouse gas (GHG) removals and emissions in afforestation and reforestation since 1990 are accounted for in meeting the Protocol's emission targets. The most evident effect of afforestation is the sequestration of atmospheric CO_2-C into the growing tree biomass. Changes in soil GHG fluxes are more difficult to predict.

In Finland the area of agricultural fields afforested within past 30 years totals over 248 000 ha. Continuous agricultural cultivation practices such as ploughing and harrowing, fertilization and liming have changed the physical, chemical and biological properties of the former forest soils (Hytönen & Wall 1997, Wall & Hytönen 2005). In organic fields addition of mineral soil has been common and the peat is generally well humified, and it has a high bulk density and high nitrogen content. The changes in soil properties are beneficial for tree growth and subsequently for C sequestration.

Peatlands in agricultural use are sources of CO_2 and N_2O, and minor sinks of atmospheric CH_4 (Nykänen et al. 1995; Maljanen 2003, Maljanen et al. 2004; Lohila et al. 2004). Soil GHG dynamics following conversion of organic or mineral soil croplands to forest are poorly understood. Gradual degradation of the ditch network and consequent decreased aeration of the soil after afforestation may lead to increased CH_4 emissions. After afforestation changes occur in the quality, quantity, timing and spatial distribution of soil C inputs. There are also abiotic factors affected in the change in soil C. On peat fields gradual changes in the soil structure and biology may change the peat decomposition rate. Carbon cycling rate and distribution among different pools/fractions of SOM change with vegetation succession in the developing forest. These changes vary from site to site depending on tree species, density of developing stands, as well as soil fertility and forest management activities (Vesterdal et al. 2002).

The aim of this study was to 1) produce estimates of the annual soil CO_2, CH_4 and N_2O emissions from typical afforested organic soil cropland in Finland and 2) to investigate changes in carbon pools over time following afforestation of mineral soil arable land.

2. Material and methods

2.1. Afforested organic soil fields

Five silver birch (*Betula pendula* Roth) and three Scots pine (*Pinus sylvestris* L.) stands aged 10-35 years growing on organic soil croplands (peat thicknesses 20-80 cm) were selected in central Finland. Soil respiration measurements were made on six study sites with a total of 30 sample plots (portable IG-meter) weekly during the growing season and monthly during the winter for two to three years (2002-2005). Aluminum tubes (Ø 31.5 cm) were inserted into the soil in order to exclude root respiration from the soil CO_2 flux. The above-ground litter and the above-ground parts of the green plants were removed to eliminate autotrophic plant respiration. Soil temperatures were measured simultaneously with the chamber measurements**.** Statistical response functions were constructed between measured soil CO_2 fluxes and simultaneously measured soil temperatures at 5 cm depth (T5), separately for each sample plot. Site-specific soil temperature data were used to reconstruct diurnal cycles of soil CO_2 efflux during the summer seasons by means of regressions equations. For winter season (November-April) the average effluxes were used.

The fluxes N_2O and CH_4 were measured during the years 2002 to 2005 from four to eight sample plots in each study site. Gas samples were collected in 60 ml plastic syringes in the field with static chamber method or gas gradient method from snow (Maljanen 2003). Samples were analysed with a gas chromatograph. The fluxes were calculated from the linear gas concentration change in time on the chamber headspace. Annual flux rates were calculated as the sum of summer and winter season fluxes for each sample plot separately in order to describe the spatial variations within the study sites.

2.2. Mineral soil afforested fields

Altogether 88 fields on mineral soil afforested 10 to 70 years ago with Scots pine, Norway spruce (*Picea abies* L.) or Silver birch were sampled and investigated. Ten soil samples were taken from each site with sample corer (Westman 1995) to the depth of 50 cm. Also 10 samples from each stand were taken from ground vegetation, surface litter and humus layer. Tree stands were measured on circular sample plots (385 m^2). Carbon content was determined in parent matter soil (20-50 cm), former tilling layer (0-20 cm) and, neo-forming humus layer, in surface litter, in ground vegetation and, in standing trees on afforested arable fields. Carbonate carbon was eliminated from the mineral soil by treating the samples with HCl.

3. Results and discussion

3.1. Organic soil afforestation areas

Soil CO_2 flux

Annual soil CO_2 fluxes on the studied sites varied from 2100 to 3500 kg CO_2-C ha a^{-1} (Fig. 1). The proportion of the annual flux emitted during the wintertime varied from 13% to 25%. The soil CO_2 fluxes after afforestation appear to be lower than fluxes measured from soils in active agricultural use (Nykänen et al. 1995, Maljanen 2003, Maljanen et al. 2004), but slightly higher than those measured on the sites drained for forestry (Minkkinen et al. 2006). Lower fluxes may result because of ceased aeration of the soil by repetitive amelioration measures, because there is no more fertilization or liming activities and because of the lower soil temperatures on the afforested sites caused by the shading effect of the growing tree stand. Peat properties on afforested organic soil croplands differ considerably from those on forestry drained peatlands. Especially mineral soil application (high ash content) on afforested organic soil croplands had a clear accelerating effect on the soil CO_2 flux.

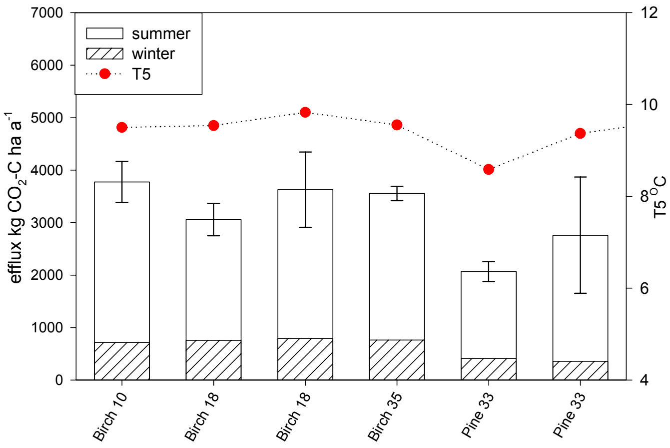

Figure 1. Average annual soil CO_2 fluxes and standard deviations (7th June 2003-o 6th June 2004). Summer (May - October) and winter (November - April) fluxes from study sites presented separately. The line depicts the average summertime soil temperature at the depth of 5 cm.

In this study only heterotrophic soil CO_2 flux was measured. In order to derive the net ecosystem C exchange (NEE), it is necessary to also consider the C input through photosynthesis and C output through leaching. When the carbon bound by the vegetation (mainly trees) is taken into account, the CO_2 balance of the sites changes considerably, and sites with highest tree yield are probably small sinks of atmospheric CO_2.

Methane

Afforested organic soil cropland sites acted mainly as minor sinks of methane similarly to forestry drained peatlands and peatlands under cultivation (Martikainen et al. 1995, Nykänen et al. 1995, Maljanen 2003, Maljanen et al. 2004) (Fig. 2). Thus afforestation does not appear to change the soil CH_4 flux on former arable lands provided that the drainage is adequate. Probably the high methane emissions observed on one of the sites were caused by the poor drainage of the site leading to anaerobic soil conditions.

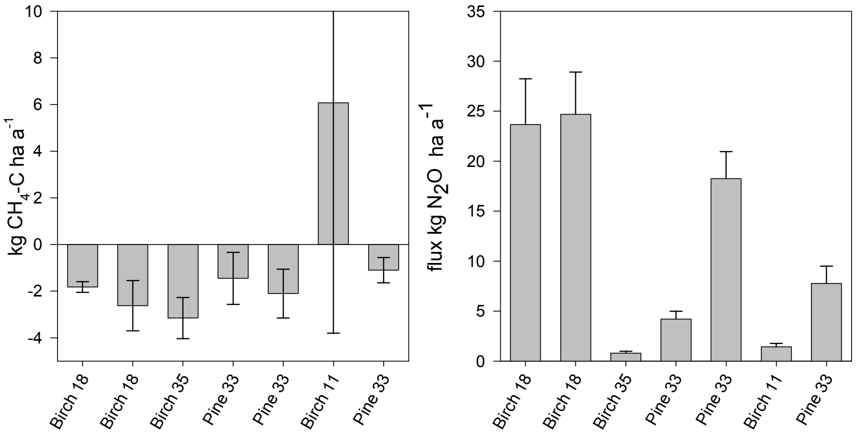

Figure 2. Mean annual soil CH_4 (A) and N_2O (B) fluxes from afforested organic soil study sites. The error bars represent the spatial variation of the fluxes within the study site expressed as standard deviations.

Nitrous oxide

All of the studied sites emitted N_2O. Annual N_2O emissions varied from 1 to 25 kg N_2O-N ha a^{-1} (Fig. 2) The N_2O emissions during winter were, on the average, 42% of the annual emissions. The results suggest that even 20-30 years after afforestation, there was still a high availability of mineral nitrogen for nitrification and denitrification responsible for the N_2O emissions. The results support earlier findings (Maljanen 2003) that the afforestation of cropland on peat soils does not abruptly terminate the N_2O emissions. The mean N_2O emissions from the sites were higher than those reported earlier for organic agricultural soils in Finland (Nykänen et al. 1995, Maljanen 2003, Maljanen et al. 2004, Regina et al. 2004), or forestry drained peatlands (e.g. Martikainen et al. 1993, Maljanen 2003).

3.2 Mineral soil afforestation areas

According to the results, carbon pools in the soil of afforested former fields are considerably higher compared with results obtained from continuously forested sites on mineral soil. In this study the carbon storage in the soils (0-50 cm) of 9-25 years old stands was on the average 8.5 kg/m^2. Carbon stores in mineral soil forests (0-50 cm) are according to Liski and Westman (1995) 3.7 – 5.3 kg/m^2. However, the field to field variation in carbon amounts was high probably reflecting differences in cultivation methods prior to afforestation. The formation of organic layer in afforested fields is a slow process. The 9-25 years old afforested fields of this study had on the average 0.3 kg/m^2 organic carbon in their organic layer. The carbon pools of the organic layer in forests (Liski and Westman 1995) have been reported to be considerably higher (1.6 – 2.2 kg/m^2). However, with increasing time since afforestation the amount of carbon bound in the newly forming humus layer (O horizon) on top of the mineral soil increased (Fig 3).

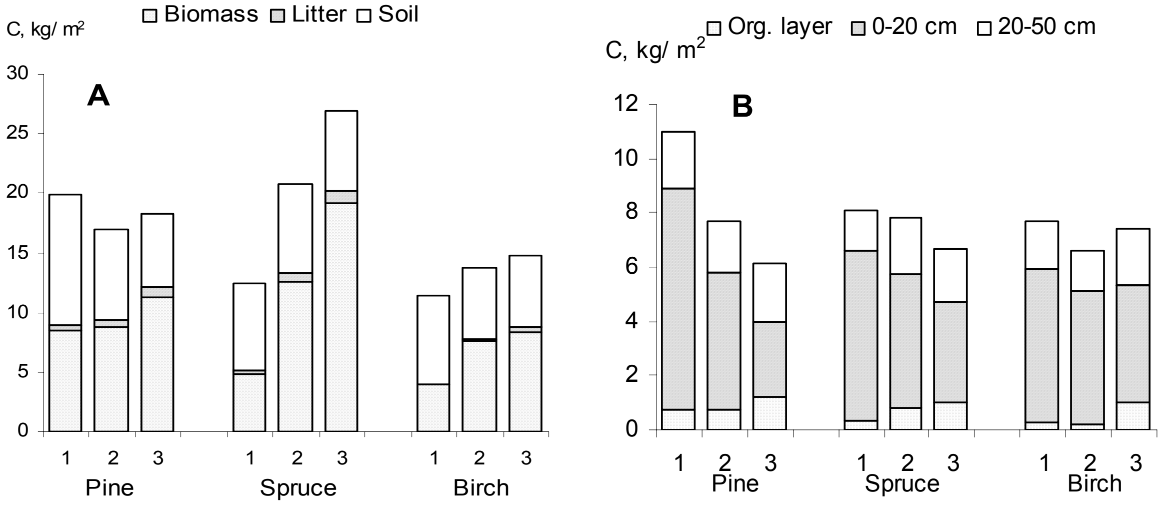

Figure 3. Organic carbon bound in 9–25 years (1), 26–40 years (2) and, more than 40 years (3) old afforestation areas planted with Scots pine, Norway spruce and Silver birch as A) total carbon pool on site distributed among biomass, in litter and in soil and as B) pools in different soil layers (O layer on top of mineral soil, 0-20 cm, 20-50 cm mineral soil layers).

In the former tilling layer (0-20 cm) the carbon pool tended to decrease with increasing stand age, while the pool below tilling layer (20-50 cm) remained rather constant. We believe that the decrease in top soil carbon pool mostly is the result of slow annual litter input from the developing tree stand: substantial pulses of litter will not reach soil until logging residues, stumps and roots are added to soil upon tree harvest. The effect of tree species is significant both in biomass and litter production. In other studies after afforestation similar initial decrease in surface soil (<10 cm or <

30 cm depth) lasting 5-35 years have generally been observed (Guo & Giffored 2002, Paul et al. 2002).

Due to the development of neo-forming organic layer in spite of the decrease in topsoil carbon stores the overall effect of afforestation on soil carbon amounts during the 50-70 year period was rather small. However, when carbon bound in the developing tree stand is taken into account, afforestation turns arable land into to a working sink for atmospheric carbon even at this time perspective, and, the efficiency of such sink would increases with time since afforestation.

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