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Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils

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Abstract

After drainage of natural boreal peatlands, the decomposition of organic matter increases and peat soil may turn into a net source of CO_2 and N_2O, whereas CH_4 emission is known to decrease. Afforestation is a potential mitigation strategy to reduce greenhouse gas emission from organic agricultural soils. A static chamber technique was used to evaluate the fluxes of CH_4, N_2O and CO_2 from three boreal organic agricultural soils in western Finland, afforested 1, 6 or 23 years before this study. The mean emissions of CH_4 and N_2O during the growing seasons did not correlate with the age of the tree stand. All sites were sources of N_2O. The highest daily N_2O emission during the growing season, measured in the oldest site, was as high as 29 mg N_2O $m^{-2}d^{-1}$. In general, organic agricultural soils are sinks for methane. Here, the oldest site acted as a small sink for methane, whereas the two youngest afforested organic soils were sources for methane with maximum emission rates (up to 154 mg $m^{-2}d^{-1}$) similar to those reported for minerogenous natural peatlands. Soil respiration rates decreased with the age of the forest. The high soil respiration in the younger sites, probably resulted from the high biomass production of herbs, could create soil anaerobiosis and increase methane production. Our results show that afforestation of agricultural peat soils does not abruptly terminate the N_2O emissions during the first two decades, and afforestation can even enhance methane emission for a few years. The carbon accumulation in the developing tree stand can partly compensate the carbon loss from soil.

Introduction

Natural boreal peatlands usually act as sinks for carbon dioxide (CO_2) and sources for methane (CH_4). In general, they are small sinks for nitrous oxide (N_2O) (Regina et al., 1996). Drainage of these soils can lead to major changes in the gas fluxes. After drainage, decomposition of organic matter increases and the sites may turn into net sources of CO_2 even though there may be a decrease in CH_4 emissions. Farmed peat soils are also major sources of N_2O (Kasimir-Klemedtsson et al., 1997).

Peatlands are typical for the northern region of the world. The total area of boreal and subarctic peatlands is 346 million hectares (Gorham, 1991). In Finland, the original peatland area covered an area of 10 million hectares. It has been estimated that a total of 0.7–1 million ha of peatlands in Finland have been cleared for agriculture (Myllys, 1996). It is estimated that about 200 000 ha peat soils were still in agricultural use in 1996, which accounts for 10% of the total arable area in Finland (Myllys, 1996). In Finland, 8% of the anthropogenic greenhouse gas load originates from these organic fields (Kasimir-Klemedtsson et al., 1997). There is currently an urgent need to develop mitigation strategies to reduce national greenhouse gas emissions according to the IPCC Kyoto Protocol (Watson et al., 2000). It is not known whether afforestation of drained organic agricultural soils could represent such a mitigation method. In general, boreal forests on mineral soils are minor sources of N_2O (Martikainen, 1996) as are the forests growing on drained peatlands without cultivation history. Only the forests on the most nutrient rich drained peatlands have some N_2O emissions (Regina et al., 1996). Forests on mineral

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soils and the well-drained peatland forests are important sinks for atmospheric methane (Crill et al., 1994; Martikainen, 1996; Martikainen et al., 1995). Approximately 80 000 hectares of the total field afforestation area in Finland (220 000 ha) are organic soils. Throughout the 1990s the areas subjected to afforestation has varied each year from 4000 to 17 700 ha of which quite a high proportion has been peat and mull fields (Hytönen, 1999). Thus, there is a need to analyze the effect of afforestation on greenhouse gas dynamics on these peat soils.

It has been shown that after drainage of natural peatlands, the developing tree stand can compensate for at least part of the increase in CO_2 production by storage of carbon in biomass (Minkkinen and Laine, 1998). However, the physical and chemical properties, and the nutrient status of agricultural organic soils differ from those of the peatland forests (Hytönen and Ekola, 1993). Therefore, the afforested farmed peat sites are usually rich in nitrogen, but quite often boron and potassium deficiencies can be disadvantageous for the growth of the stands. Furthermore, tilling, fertilizing, liming and other cultivation practices have changed the original soil properties, especially the properties of the topsoil (0–20 cm) (Wall and Hytönen, 1996; Wall and Heiskanen, 1998).

Afforestation changes the physical, chemical and biological properties of the cultivated soil. The absence of ploughing decreases the porosity and aeration of peat (Wall and Heiskanen, 1998). Therefore, anaerobic processes, such as denitrification and methane production, could be favored by afforestation. On the other hand, the increased immobilization of nitrogen would decrease the availability of inorganic nitrogen for nitrification and denitrification processes associated to N_2O production. We used a dark chamber technique to measure the fluxes of nitrous oxide, methane and carbon dioxide in afforested peat soils in western Finland, and studied if the fluxes are dependent on the age of the afforested site.

Methods

Experimental sites

The experimental sites are located in northwest Finland (64° 06′ N, 24° 21′ E). The mean annual temperature and precipitation in the area are 2.0 °C and 544 mm, respectively. The sites were used for agriculture and were afforested after cultivation terminated (Table 1). The studied fields were situated in the same peatland area, 200 m from each other. Site 1 was afforested with birch one year before the measurements started. Sites 2 and 3 had been afforested with pine 6 and 23 years before the flux measurements (Table 1). The sites were not fertilized after afforestation. The peat depths of soils were 3.0, 1.0 and 2.8 m in sites 1, 2 and 3, respectively.

Soil physical and chemical analysis

Close to each chamber, two volumetric soil samples were taken from soil layers of 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm. In the calculation of the results in Table 2, the layers of 0–20 cm and 20–40 cm were compared. The gravimetric moisture content was determined by drying soil samples for 24 h at 65 °C, recommended for organic soils (Kutilek and Nielsen, 1994). Soil pH was measured from soil-water suspensions (1:5 v/v). The organic matter content was determined as a loss of ignition (550 °C, 8 h). Soil samples were analyzed for their total (HCl extraction of ignition residue) and acid ammonium acetate (pH 4.65) extractable nutrient concentrations with an atomic absorption spectrophotometer (K, Ca and Mg) or with a spectrophotometer (N and P) (Halonen et al., 1983). Total N was analyzed with the Kjeldahl method. NH_4^+ and NO_3^- were extracted from soil by shaking samples in 1 m KCl (solution to soil ratio 5:1, v/v) for 1 h (100 rpm), and then filtered (Schleicher & Schuell 589^3 filter paper). The extracts were kept frozen until analyzed for NO_3^- and NH_4^+ by a continuous flow analyzer (Bran & Luebbe TRAACS-800).

Flux measurements

Fluxes of CH_4, N_2O and CO_2 were measured with a dark static chamber method (Martikainen et al., 1995; Nykänen et al., 1995) from June to October in 1996 and 1997. Permanent aluminum collars (60 cm × 60 cm, height 30 cm) were installed into the soil in June 1996. Flux measurements from four flux chambers at each site were made four times in 1996 and six times in 1997 between 10:00 a.m. and 2:00 p.m. During sampling, an aluminum chamber (60 cm × 60 cm, height 20 cm, equipped with a fan) was placed over the aluminum collars, which had water filled grooves in the upper end to ensure gas tightness. Gas samples were taken with 50 ml polypropylene syringes (Terumo) equipped with three-way stopcocks (Connecta)

Table 1. General characteristics and vegetation cover of the study sites

	Site 1	Site 2	Site 3
Cultivation ended	1994	1988	1972
Afforestation	1995	1990	1973
Water table level (m)[a]	0.31 (0.10, 0.88)	0.38 (0.04, 0.80)	0.44 (0.23, 0.76)
Mean soil temperature (°C)[b]	8.4 (0.0, 16.9)	8.1 (0.4, 15.4)	7.6 (0.2, 14.3)
Dominant tree species	*Betula pubescens*	*Pinus sylvestris*	*Pinus sylvestris*
Aboveground tree biomass ($kg\ ha^{-1}$)	100	2500	40 600
Plant species		*Mean coverage (%)*	
Ranunculus acris	30	13	1
Deshampsia caespitosa	24	33	20
Phleum pratense	13	4	0
Poa spp.	7	1	0
Epilobium palustre	4	1	0
Rumex acetosa	2	3	4
Juncus filiformis	2	4	1
Agrostis spp.	1	15	0
Epilobium angustifolium	1	1	2
Cirsium spp.	0	4	0
Achillea ptarmica	0	5	0
Equisetum spp.	0	<1	0
Galeopsis spp.	0	1	0
Rubus arcticus	0	0	18
Viola palustris	0	9	18
Calamagrostis arundinaceae	0	0	13
Salix spp.	2	0	0
Betula pubescens	3	1	4
Picea abies	0	0	<1
Dryopteris carthusiana	0	0	2
Marchantia polymorpha	0	5	0
Polytrichum spp.	0	0	9
Pleurozium schreberi	0	0	35

[a] Mean water table level for the period from end of May to beginning of October. Minimum and maximum values are given in the parenthesis.
[b] Mean soil temperature at a depth of 5 cm for the period of end May to beginning October. Minimum and maximum values are given in the parenthesis.

3, 10, 15 and 20 min after the chambers were installed. The samples were analyzed within 24 h after sampling with a gas chromatograph (Hewlett-Packard 5890 Series II) equipped with flame ionization (FI), electron capture (EC) and thermal conductivity (TC) detectors (Nykänen et al., 1995) and the flux rates were calculated from the linear change in the gas concentrations. The daily CO_2 emissions were calculated by a linear regression (SPSS) with the air temperature as an independent variable using the actual field data separately for each soils (see Table 3). This was done by calculating the parameters (b_0, b_1) of the formula:

$$cCO_2 = \exp (b_0 + b_1\ T_{air}),$$

where T_{air} is the measured actual air temperature during the measurements. The daily mean cCO_2 rates were calculated applying the mean daily temperature in the equation. Ground water level (WT) was measured from perforated groundwater wells (diameter 3 cm) near each collar during every sampling day. The composition and coverage of vegetation was studied from each (0.36 m^2) gas sampling collar, 4 collars per site, in 1997.

Statistical methods

The results were analyzed by one-way analysis of variance and correlation analysis (2-tailed Pearson cor-

Table 2. Physical and chemical soil characteristics of the study sites

Study site	Soil layer 0–20 cm				Soil layer 20-40 cm			
	1	2	3	*F*	1	2	3	*F*
BD, g cm^{-3}	0.25	0.29	0.24	3.59	0.15^a	0.22^b	0.25^b	5.81*
pH	5.3^a	4.9^b	4.7^b	13.32**	4.7	4.6	4.7	1.41
OM,%	79^a	68^a	60^b	5.80*	93^a	83^a	71^b	7.37**
Tot N, kg ha^{-1}	10 800^a	9940^b	8230^b	9.08**	6360	8100	9780	0.80
Tot P, kg ha^{-1}	840	820	720	2.31	290^a	440^a	730^b	9.09**
Tot K, kg ha^{-1}	150^a	300^b	270^b	11.24**	40^a	150^a	230^b	9.52**
Tot Ca, kg ha^{-1}	4780^a	3420^b	1750^c	32.07*	1730	2200	2010	1.18
Tot mg, kg ha^{-1}	780^a	1390^b	890^a	4.34*	1400^a	790^b	780^b	3.67*
NH_4^+, mg g^{-1}	6.2	5.2	4.8	0.32	ND	ND	ND	ND
NO_3^-, mg g^{-1}	3.0	5.9	3.4	0.90	ND	ND	ND	ND
Soil moisture,%	72^a	65^b	71^a	27.29**	ND	ND	ND	ND

BD = Bulk density.
OM = Total organic matter (loss of ignition).
ND = Not determined.
The differences between the soil layers of various sites were analyzed by the analysis of variance (** $p< 0.01$, * $p<0.05$). The values with a common letter as superscript do not differ at a statistical significance of $p < 0.05$ in Tukey's test. The statistical difference between the groups increases with increasing *F* value.

Table 3. Mean, minimum and maximum fluxes of CH_4, cCO_2 and N_2O in the two summer seasons

Year/	N_2O (mg m^{-2} d^{-1})			CH_4 (mg m^{-2} d^{-1})			cCO_2(g m^{-2} d^{-1})^a		
Site	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1996									
1	1.7	−1.0	16.9	3.7	−2.7	21.1	21.2	8.0	42.1
2	0.8	−0.1	2.4	1.4	−1.2	8.9	18.4	9.5	29.7
3	1.3	−0.1	4.9	0.1	−1.5	2.8	11.0	6.6	16.1
1997									
1	1.5	−0.2	28.8	11.6	−1.4	154.3	31.3	6.6	94.8
2	0.8	−0.0	2.5	10.7	−0.7	119.6	23.6	8.4	51.8
3	4.6	0.2	25.5	−1.2	−8.6	0.37	13.4	6.0	24.9

[a] The daily cCO_2 production was calculated by linear regression with air temperature as an independent variable. The equations were ln cCO_2 = 7.899+ 0.142 T_{air}(R^2= 0.77), ln cCO_2 = 8.147+ 0.096 T_{air} (R^2= 0.76) and ln cCO_2 = 8.219 + 0.076 T_{air} (R^2= 0.56) for the sites 1, 2 and 3, respectively.

relation, SPSS for Windows 9.0.1, SPSS Inc.). Principal Component Analysis (PCA) (SPSS for Windows 9.0.1, SPSS Inc.) was used to show the interactions between environmental factors and the gas fluxes.

Results

Weather conditions and soil physical and chemical properties

The air temperature from June to August was 2.3 °C higher in 1997 than the long time average of 14.1 °C, (reference period 1961–1990, Finnish Meteorological Institute). In 1996 (June – August), the temperature corresponded to the long-term average temperature. Precipitation during these months was lower in 1997 (150 mm) than in 1996 (215 mm). The average precipitation in reference period of 1961–1990 for June–August was 195 mm (Finnish Meteorological Institute, 1991).

The mean WT was lowest at the oldest forest site and highest at the youngest site (Table 1). Soil temperature decreased with the forest age (Table 1). The bulk density of the topsoil (0–20 cm) was nearly the same at all sites, but the 20–40 cm layers of sites 2 and 3 had lower bulk density than site 1 (Table 2). The soil moisture in the topsoil during the growing season was lowest at site 2. The soil pH varied from 4.7 to 5.3, decreasing in the topsoil with the age of afforestation (Table 2). The youngest site had the highest, and the oldest site the lowest content of organic matter in soil (Table 2). The amounts of N, P and Ca in the topsoil (0–20 cm) decreased with the age of the forest (Table 2). The content of K was lowest in the youngest site. There were no statistical differences in the amounts of NH_4^+ and NO_3^- between the sites.

Botanical characteristics

Grasses were the most common plant species in the field layer at sites 1 and 2, whereas in the oldest forest more mosses and ferns were found (Table 1). *Ranun-*

culus acris and *Deschampsia caespitosa* were the most common vascular plants at site 1, and *Deschampsia caespitosa* and *Agrostis* at site 2. The most common plants in the oldest forest were *Deschampsia caespitosa, Rubus arcticus* and *Viola palustris*.

Nitrous oxide fluxes

All the sites were sources of N_2O (Table 3, Figure 1), though there was a wide spatial and temporal variation. There were statistical differences between the sites (one-way analysis of variance, F = 10.64, P = 0.000). There was no distinct correlation between the age of afforestation and the N_2O fluxes. The highest mean N_2O emission occurred at the oldest forest (Table 3), although the highest peak was found for the youngest site. The mean N_2O emission for site 2 was lower than those for sites 1 and 3. The N_2O fluxes for all sites decreased towards autumn after the peak during the spring thaw at the beginning of June (Figure 1). There were no flux measurements during winter. The results of principal component analysis (PCA) showed that N_2O fluxes had interactions with WT and the succession of vegetation (Figure 2). *Rubus arcticus, Viola palustris, Dryopteris carthusiana, Rumex acetosa* and mosses were common in the oldest forest site with the lowest mean WT and highest mean N_2O fluxes.

Methane fluxes

There were differences in the CH_4 fluxes between the sites (variance analysis, F = 8.03, P = 0.001). The oldest site 3, acted as a small sink or source for methane, whereas the two younger sites were sources of methane (Table 3). The highest methane emissions, up to 154 mg m^{-2} d^{-1}, were measured at sites 1 and 2 in the middle of August 1997 during a warm and dry period with the lowest WT. PCA analysis showed that CH_4 fluxes, similarly to CO_2 fluxes, correlated positively with the occurrence of *Agrostis* spp., *Achillea ptarmica, Phleum pratense, Epilobium palustre, Poa* spp. and *Ranunculus acris* (Figure 2), common in the two youngest sites.

Community CO_2 production

Carbon dioxide from aerobic and anaerobic decomposition processes, respiration of soil animals, dark respiration of plants as well as CO_2 from root respiration are included to the CO_2 fluxes measured with the dark static chambers. This CO_2 flow is termed here as community CO_2 production (cCO_2). Tree stands are not included in the measured cCO_2. The cCO_2 production correlated positively with air and soil (depth 5 cm) temperatures (R^2= 0.80 and 0.87, respectively). Therefore the daily cCO_2 emissions at different sites were calculated with linear regression models (SPSS) in relation to air temperature (Table 3). The highest measured cCO_2 (1100 mg CO_2 m^{-2} h^{-1}) took place in August 1997 at sites 1 and 2, whereas at site 3 the highest cCO_2 flux was measured in September. The mean cCO_2 flux were 47, 29 and 21% higher during the warm summer of 1997 than in the cooler summer of 1996 at sites 1, 2 and 3, respectively. The cCO_2 decreased with the age of the forest (Table 3). PCA analysis showed that cCO_2 flux is associated with CH_4 flux and the occurrence of *Agrostis* spp., *Achillea ptarmica, Phleum pratense, Epilobium palustre, Poa* spp. and *Ranunculus acris.*

Discussion

The N_2O emissions from the afforested sites were even greater than those reported earlier for organic agricultural soils in Finland (Nykänen et al., 1995), or forested peatlands (Martikainen et al., 1993; Regina et al., 1996, 1998). There was no decrease in the N_2O emissions with age of the afforestation. In fact the highest N_2O emissions were found at the oldest site 3 during the warm summer of 1997. The sites had no nitrogen fertilization and the nitrogen deposition was low. Therefore, the results suggest that there still was after 24 years of afforestation a high availability of mineral nitrogen for nitrification and denitrification responsible for the N_2O production. The results do not allow differentiate the N_2O produced in nitrification and denitrification. The PCA analysis shows that the N_2O emissions increased with lowering in water table. This would reflect increase in nitrification with decreasing water table. It is known that water table level and associated NO_3^- production highly regulate N_2O production in peat soils (Regina et al., 1999). The characteristics of litter from various tree species vary and could affect the soil chemistry and biology. Birch litter is better decomposable than the litter from coniferous trees (Mikola, 1955; Priha et al., 1999), and could thus favor the N_2O production. The youngest site planted with birch had higher N_2O fluxes than the site 2, which was afforested with pine. However, the highest mean N_2O emissions were found from the oldest pine site, therefore the tree species were not closely associated to the N_2O emissions.

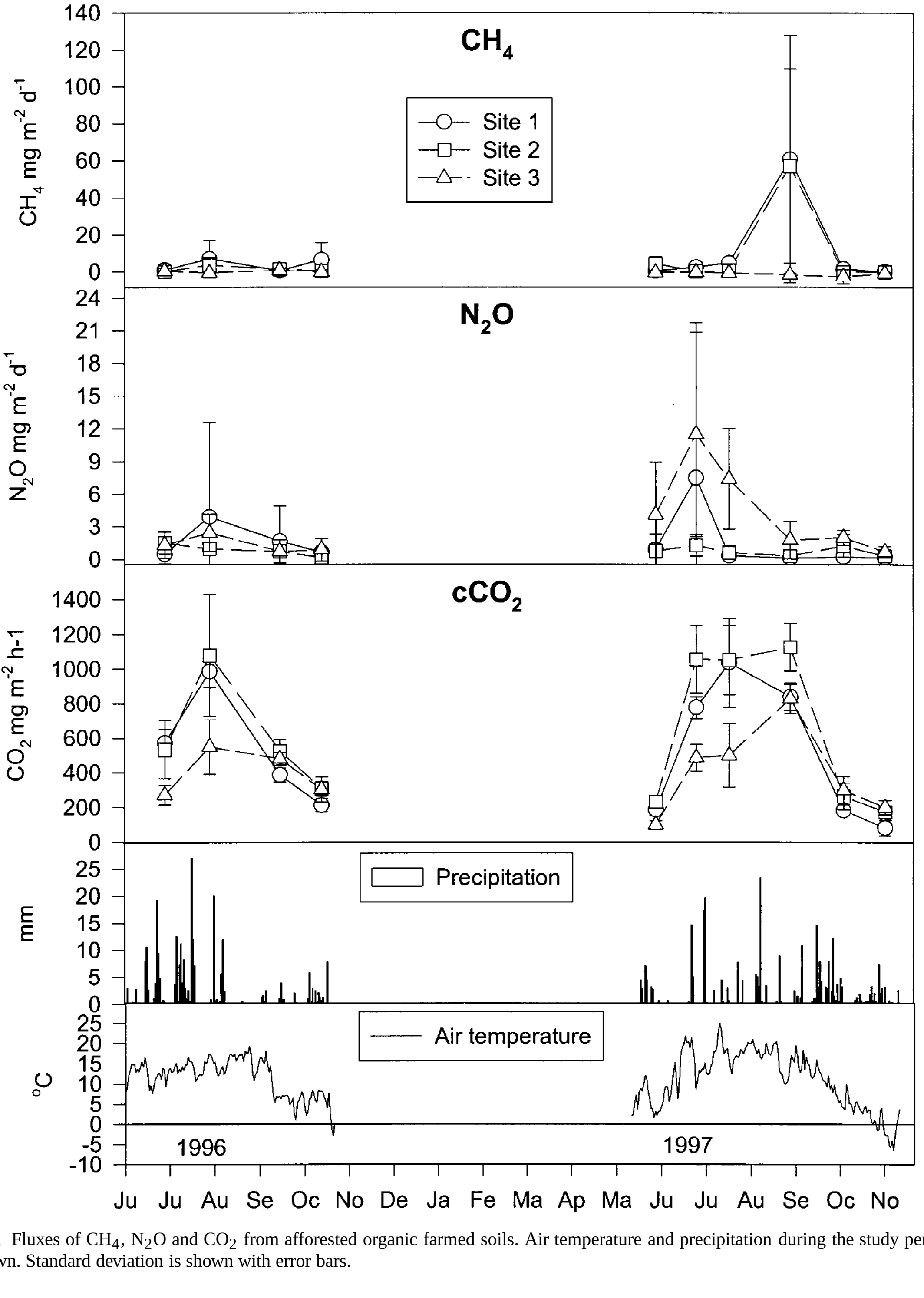
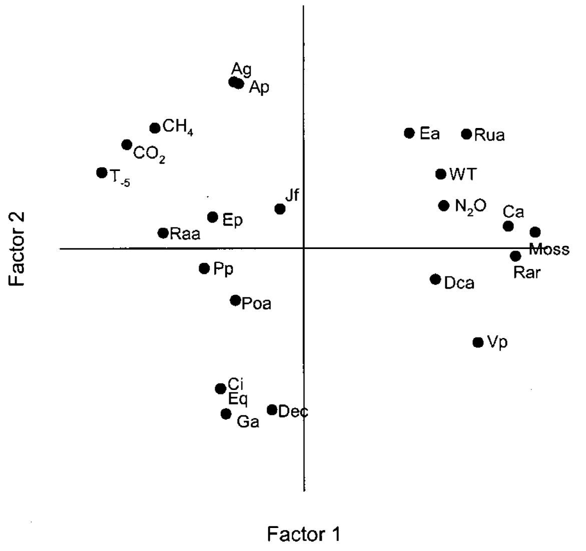


Figure 1. Fluxes of CH_4, N_2O and CO_2 from afforested organic farmed soils. Air temperature and precipitation during the study periods are also shown. Standard deviation is shown with error bars.

The oldest forest soil (3) acted as a sink for methane, but the two younger forest sites (1 and 2) were mainly sources of CH_4. In general, well-drained Finnish peatland forests are sinks for methane (Crill et al., 1994; Martikainen et al., 1995) and agricultural peatlands are small sinks or sources for CH_4 (Nykänen



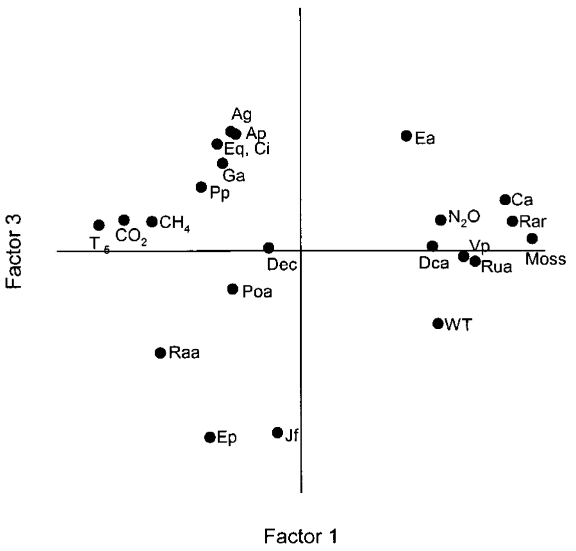


Figure 2. Interactions between CH_4, N_2O and CO_2 fluxes, soil temperature (T_{-5cm}), water table level (WT) and plant species using principal component analysis (PCA). WT is expressed as a positive value showing the distance between water table level and soil surface. In the PCA analysis, the two first components explained 48% of the variance and when the third component was included into the analysis 61% of the variance was explained. Ag= *Agrostis,* Ap= *Achillea ptarmica,* Ca=*Calamagrostis arundinaceae,* Ci=*Cirsium,* Dca=*Dryopteris carthusiana,* Dec=*Deshampsia caespitosa,* Ga=*Galeopsis,* Ea=*Epilobium angustifolium,* Ep=*Epilobium palustre,* Eq=*Equisetum,* Jf=*Juncus filiformis,* Pp=*Phleum pratense,* Poa=*Poa,* Raa=*Ranunculus acris,* Rar=*Rubus arcticus,* Rua=*Rumex acetosa,* Vp=*Viola palustris,* Moss= *Marchantia polymorpha, Polytrichum, Pleurozium schreberi.*

et al., 1995). Priemé at al. (1997) showed that after abandonment of agriculture, CH_4 oxidation rate increases very slowly. This could be true also for the afforested peat fields, and it may be associated to the CH_4 emissions from many years after afforestation. In 1996, the methane emissions from the two youngest forest sites were small, less than 20 mg $m^{-2}d^{-1}$, though more than emissions for farmed organic soils (Maljanen M, pers. comm.; Nykänen et al., 1995). In August 1997, during a warm period, very high methane emissions were observed at these sites, similar to those found for minerogenous natural peatlands in Finland (Nykänen et al., 1998). The probable reason was the high oxygen consumption by the high respiration activity in warm soil, which causes oxygen deficiency in soil. The anaerobiosis and methane production were favoured by the low gas diffusion rate in peat soil with high bulk density (Wall and Heiskanen, 1998).

The community CO_2 production was here high, nearly similar as found for cultivated organic soils (Glenn et al., 1993; Koizumi et al., 1999; Nykänen et al., 1995). The cCO_2 flux was highest at the younger sites, in spite they had a high WT, indicating that the decomposition rate was faster in these sites. The large number or herbs and grasses at the younger sites 1 and 2 increase the availability of fresh organic carbon for degradation as shown by the high cCO_2 production and, perhaps, CH_4 release. The high mineralisation rate of organic matter decreases soil aeration, which further enhances CH_4 production but decreases CH_4 oxidation. The higher temperature in the soil of the young sites (see above) also enhances microbial activities (Figure 2).

Vascular plants, which are known to conduct CH_4 and CO_2 from the deeper soil layers (Thomas et al., 1996), were more common at the younger sites 1 and 2. Methane and cCO_2 fluxes had positive interactions with some common field plant species as *Ranunculus acris, Phleum pratense, Poa* spp. and *Agrostis* spp. (Figure 2). The methane emissions from these sites can be associated with the mechanical gas transportation by plants (Thomas et al., 1996; Whiting and Chanton, 1992) together with the favourable conditions for methane production. The change from field vegetation to forest vegetation on afforested agricultural soils is a very slow process; it can take 20 or even 50 years (Hytönen, 1999; Wall, 1998). In site 1, there was still quite much *Phleum pratense* since there had been cultivation of hay. Site 2 had also still high coverage of grasses. The oldest site 3 contained least grasses and forest vegetation dominated, especially *Pleurozium schreberi* in the moss layer.

The atmospheric impact of afforested organic soils highly depends on the carbon accumulating in the developing tree stand. The annual biomass increment of 24 years old pine stand is on average 14.5% (Nyyssönen and Mielikäinen, 1978). The root biomass of pine is estimated to be 60% of the stemwood biomass (Kauppi et al., 1995), here 8800 kg C ha^{-1}. The annual increase in the below ground and above ground tree biomass is then 4200 kg C ha^{-1} yr^{-1} in site 3. This can be an overestimate because the calculations are based on tree stands growing on mineral soils and there is no data for organic soils. The Finnish organic agricultural soils without plants are known to release annually from 4000 to 10 000 kg CO_2-C ha^{-1} (Maljanen M, pers. comm.; Nykänen et al., 1995). The C accumulation in the tree biomass could thus compensate part of the C release in soil respiration. However, more experimental data is needed for the long-term CO_2, CH_4 and N_2O dynamics to conclude the effectiveness of this mitigation strategy for agricultural organic soils.

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