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Afforestation does not necessarily reduce nitrous oxide emissions from managed boreal peat soils

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Abstract Pristine peatlands have generally low nitrous oxide (N_2O) emissions but drainage and management practices enhance the microbial processes and associated N_2O emissions. It is assumed that leaving peat soils from intensive management, such as agriculture, will decrease their N_2O emissions. In this paper we report how the annual N_2O emission rates will change when agricultural peat soil is either left abandoned or afforested and also N_2O emissions from afforested peat extraction sites. In addition, we evaluated a biogeochemical model (DNDC) with a view to explaining GHG emissions from peat soils under different land uses. The abandoned agricultural peat soils had lower mean annual N_2O emissions (5.5 ± 5.4 kg N ha^{-1}) than the peat soils in active agricultural use in Finland. Surprisingly, N_2O emissions from afforested organic agricultural soils (12.8 ± 9.4 kg N ha^{-1}) were similar to those from organic agricultural soils in active use. These emissions were much higher than those from the forests on nutrient rich peat soils. Abandoned and afforested peat extraction sites emitted more N_2O, (2.4 ± 2.1 kg N ha^{-1}), than the areas under active peat extraction (0.7 ± 0.5 kg N ha^{-1}). Emissions outside the growing season contributed significantly, 40% on an average, to the annual emissions. The DNDC model overestimated N_2O emission rates during the growing season and indicated no emissions during winter. The differences in the N_2O emission rates were not associated with the age of the land use change,

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vegetation characteristics, peat depth or peat bulk density. The highest N_2O emissions occurred when the soil C:N ratio was below 20 with a significant variability within the measured C:N range (13–27). Low soil pH, high nitrate availability and water table depth (50–70 cm) were also associated with high N_2O emissions. Mineral soil has been added to most of the soils studied here to improve the fertility and this may have an impact on the N_2O emissions. We infer from the multi-site dataset presented in this paper that afforestation is not necessarily an efficient way to reduce N_2O emissions from drained boreal organic fields.

Keywords Agriculture · Forestry · N_2O · Peatland · Water table · Carbon · Nitrogen · Nitrate · pH · Winter

Introduction

Nitrous oxide (N_2O), an effective greenhouse gas (GHG) (Solomon et al. 2007), is produced by microbial nitrification and denitrification in soil (Davidson 1991). In organic soils the high availability of mineral nitrogen and substrates favour the microbial processes associated with N_2O production. Therefore, drained organic soils with high N_2O emissions can have a great regional or national importance in the atmospheric N_2O load (Kasimir Klemedtsson et al. 1997). Peat soils drained for agriculture are responsible for a large part of the global N_2O emissions from soils (Kroeze et al. 1999). When peat soils are drained and used for cultivation, the lowered water table level, repeated ploughing, fertilization and liming (leading to an increase in soil pH) enhance the decomposition of nitrogen-rich organic matter and could potentially increase N_2O emissions. However, the environmental factors, which control N_2O production and emissions, form a complex network (e.g. Groffmann et al. 2000; Nishina et al. 2009) making it difficult to predict the actual N_2O fluxes.

About 0.7 M ha from the original peatland area of 10.4 M ha have been cleared and drained for agriculture in Finland (Turunen 2008). Nearly half of these soils have been abandoned, afforested or have now been classified as mineral soils resulting from the fast decomposition of their organic matter, decrease in the peat depth and mixing of the remaining peat with mineral subsoil. About 300,000 ha of organic soils are still in agricultural use (Myllys 1996; Myllys and Sinkkonen 2004). Peatlands have been drained also for peat extraction for energy production, 63,000 ha in Finland (Turunen 2008). By the year 2020 about 45,000 ha will be removed from peat extraction in Finland (Turveteollisuusliitto 2009). The land owner decides the after-use option of these peat extraction sites, but afforestation has been the most common one.

The mean annual N_2O emissions from Finnish organic agricultural soils in active use (grassland, cropland) are 11.8 ± 8.8 kg N ha^{-1} (Nykänen et al. 1995; Regina et al. 1996, 2004; Maljanen et al. 2003a; 2004, 2009). However, there are only few studies on the N_2O emissions from boreal afforested agricultural peat soils (Maljanen et al. 2001; von Arnold et al. 2005a, b). Furthermore, the winter emissions are still poorly quantified even though these emissions may contribute significantly to the annual N_2O budget (e.g. Maljanen et al. 2009).

Peat extraction areas also are sources of N_2O (Alm et al. 2007; Nykänen et al. 1996; Hyvönen et al. 2009), but their annual emissions (from 0.3 to 2.0 kg N_2O-N ha^{-1}) are much lower than those measured from agricultural soils. In year 2004 the N_2O emissions in Finland have been estimated to be 1.06 and 0.01 Tg as CO_2 equivalents from cultivated organic agricultural soils and peat extraction areas, respectively (Lapveteläinen et al. 2007).

It has been suggested that afforestation of agricultural peat soils could offer a possibility to mitigate GHG emissions from these soils. After the cultivation practices have ceased, the secondary vegetation succession starts. Grasses and herbs dominate in field vegetation for decades (Törmälä 1982) and open ditches are the first habitat for the pioneer tree species (birch, willows) (Hytönen 1999). If the abandoned peat field or peat extraction area is afforested, soil preparation by ditch-mounding or ploughing is followed by planting of the seedlings (Hytönen 2008; Aro 2008). Peat extraction areas can also be afforested by sowing or using natural regeneration (Aro 2008). The most common tree species used in Finland have been Scots pine (*Pinus sylvestris* L.) and Silver birch (*Betula pendula* Roth.) even though nowadays Norway spruce (*Picea abies* L.) is mostly recommended for peat fields. Subsequently, fertilization with mainly PK-fertilizers may be carried out, especially on peat extraction areas with deep peat layers (Hytönen 2008; Aro 2008).

We hypothesize that the N_2O will decrease when the soil management has completely ceased for several decades. With a view to evaluate this hypothesis, we measured annual N_2O emissions from five abandoned and seven afforested agricultural soils and compared these fluxes with those under active use (e.g. agriculture). Also N_2O emissions from five abandoned and afforested peat extraction sites were measured to study the effect of afforestation from soils without any cultivation history. Moreover, as the study sites exhibited wide variability in N_2O emissions, we simulated GHG exchange from two different sites with contrasting N_2O emission characteristics employing an existing, widely used DNDC biogeochemical model.

Materials and methods

Study sites

N_2O emissions were measured from June 2002 to June 2005 on five abandoned organic agricultural soils and on four afforested organic agricultural soils. In addition, N_2O measurements were made on five afforested (abandoned) peat extraction sites and on three additional afforested organic agricultural soils from June 2003 to June 2005. The site characteristics are shown in Table 1.

The abandoned (AB) and afforested (AF) agricultural sites were located in western Finland in Kannus (63°54′N, 23°56′E) and in Ylivieska

Table 1 Site characteristics (soil sampling depth 0–20 cm)

Site	Tree	SA (years)[c]	SV (m^3 ha^{-1})[c]	PD (cm)[d]	BD (g cm^3)[d]	OM (%)[d]	C:N[d]	P_{TOT} (mg g^{-1})	K_{TOT} (mg g^{-1})	Soil pH[d]
Afforested agricultural soils										
AF1	Birch	18	16	56–89	0.25	74	12.9	2.9	0.6	4.7
AF2	Birch	18	27	43–65	0.25	69	17.9	2.6	0.8	4.6
AF3[a]	Pine	33	137	46–55	0.18	93	18.8	1.0	0.3	4.2
AF4	Pine	33	75	62–75	0.28	68	17.4	1.8	0.7	4.1
AF5	Birch	35	193	32–40	0.26	72	19.2	1.9	0.8	4.1
AF6	Pine	33	104	>200	0.24	60	18.0	1.6	0.7	4.7
AF7	Birch	11	12	>200	0.25	79	18.9	1.9	0.5	5.4
Abandoned agricultural soils										
AB1	–	–	–	30	0.38	52	18.8	1.5	1.6	4.9
AB2	–	–	–	20–30	0.40	43	19.0	0.1	1.1	5.0
AB3	–	–	–	30	0.38	44	18.3	0.2	1.7	5.9
AB4	–	–	–	30	0.30	61	16.3	0.2	0.7	4.5
AB5	–	–	–	80	0.42	41	19.2	0.1	2.5	4.3
Afforested peat extraction sites										
AFC1[a]	Pine	18	24	5–60	0.19	84	26.5	0.5	0.2	4.4
AFC2[a]	Birch	30–40	365	40–72	0.17	94	23.4	0.6	0.2	4.0
AFC3[a]	Pine	43	248	38–55	0.17	94	24.5	0.5	0.2	3.9
AFC4[b]	Birch	27	86	55–77	0.57	23	23.3	0.5	0.3	4.1
AFC5[b]	Pine	29	163	41–69	0.36	42	23.5	0.5	0.3	4.6

AF Afforested agricultural soils, *AFC* afforested peat extraction site, *AB* abandoned agricultural soils, *SA* stand age, *SV* stand volume, *PD* peat depth, *BD* peat bulk density, *OM* organic matter content

[a] No mineral soil addition on peat

[b] Mineral sub-soil from ditches had been lifted on peat surface and mixed with peat

[c] Measured in 2005

[d] Measured in 2002

Table 2 The three most dominant plant species in order of coverage in AB and AF sites during the growing season 2003

Site			
AB1	*Cirsium palustre*	*Juncus filiformis*	*Epilobium palustre*
AB2	*Juncus filiformis*	*Deschampsia cespitosa*	*Cirsium palustre*
AB3	*Elymus repens*	*Poa pratensis*	*Achillea ptarmica*
AB4	*Deschampsia cespitosa*	*Rubus arcticus*	*Epilobium angustifolium*
AB5	*Epilobium angustifolium*	*Agrostis capillaries*	*Rubus arcticus*
AF1	*Rubus arcticus*	*Viola palustris*	*Galeopsis bifida*
AF2	*Epilobium angustifolium*	*Viola palustris*	*Poa pratensis*
AF3	*Dryopteris carthusiana*	*Brachythecium* spp.	*Pleurozium schreberi*
AF4	*Deschampsia cespitosa*	*Pleurozium schreberi*	*Rubus arcticus*
AF5	*Brachythecium* spp.	*Agrostis stolonifera*	*Agrostis capillaries*
AF6	*Brachythecium* spp.	*Pleurozium schreberi*	*Viola palustris*
AF7	*Brachythecium* spp.	*Viola palustris*	*Rumex acetosa*

(64°06′N, 24°21′E). The AB and AF sites were drained and used for cultivation of grass and cereals for decades before they were abandoned 20–40 years ago. During the agricultural phase, some mineral soil had been mixed with peat (except in the site AF3, see Table 1) and recommended dose of fertilizers has been used to improve the soil properties for cultivation. In the AB sites no fertilization or ploughing activities have been carried out since agricultural practises have ended. These sites were naturally vegetated; the most dominant plant species are shown in Table 2. Soil pH varied from 4.1 to 5.4 and the mean soil C:N ratio was 18.3 (Table 1).

Prior to afforestation, the soil at AF sites was prepared by single mouldboard ploughing and the sites were planted with silver birch (*Betula pendula* Roth.), downy birch (*Betula pubescens* Ehrh.) and Scots pine (*Pinus Sylvestris* L.) (Table 1). No fertilisation or ploughing activities have been carried out since then. Soil pH varied from 4.3 to 5.9 and the mean soil C:N ratio was 17.6 (Table 1).

Afforested peat extraction (AFC) sites are located, no more than one km apart from each other, in a peat production area called Aitoneva, in Kihniö, in central Finland (62°12′N, 23°18′E). Peat was extracted 15–20 years prior to afforestation. The depth of the remaining peat layer was from 5 to 77 cm (Table 1). All sites had been fertilized with P and K upon afforestation. In the AFC4 and AFC5 sites, the mineral sub-soil from ditches was lifted onto the peat surface and mixed with peat with a rotavator before afforestation resulting in a lower organic matter content in the surface (0–20 cm) peat layers. Soil pH ranged from 3.9 to 4.1 and the mean C:N ratio was higher than that in the abandoned agricultural sites (24.2, Table 1).

Soil chemical and physical characteristics and weather data

Soil pH was measured in distilled-deionized water from dried soil samples using a 1:2.5 v:v soil solution suspension. The bulk density of the soil was calculated as the ratio of dry mass (dried at 105°C) to the volume of the sample. The organic matter content was determined as loss-on-ignition (550°C, 8 h). Content of soil total C was determined with LECO CHN-1000 or LECO CHN-2000. The total N concentrations of the soil samples were determined by the Kjeldahl method. The soil samples were analysed for their total concentrations of P and K (HCl extraction of ignition residue) according to Halonen et al. (1983).

Soil NO_3^- and NH_4^+ contents were measured in the early summer and in the autumn from the AB and the AF sites and once from the AFC sites. NH_4^+ was extracted with 1 M KCl and NO_3^- with H_2O (solution to soil ratio 5:1, v:v). Slurries were shaken for 1 h at 175 rpm and then filtered (Whatman Blue ribbon 589^3). The extracts were frozen until analyzed for NO_3^- with an ion chromatograph and for NH_4^+ with a spectrophotometer according to Fawcett and Scott (1960).

Soil temperatures from of 2, 5 10 and 15 cm depths were measured from each sub plot with a Fluke 51 (Fluke Corporation, USA), or similar thermometer from the unfrozen soil every time when gas samples were taken for the flux measurements. Soil

temperatures were also recorded with i-button® temperature loggers at the AFC and AB sites, and the AF1–AF5 sites. Soil temperature was monitored at the AB3 site continuously using Campbell 107 soil temperature sensors. Air temperature and precipitation data was collected by the Finnish Meteorological Institute at Toholampi weather station near Kannus and Ylivieska study sites and at Karvia Alkkia station about 30 km from the Aitoneva study site. Water table level was measured from ground water pipes from the subplots and the depth of soil frost was measured using frost-depth gauges filled with methylene blue water solution (Gandahl 1957). Wet deposition was monitored with three replicate collectors in the AB sites sampled during seven periods between May 7 and September 4, 2003. Electrical conductivity, pH, NO_3^--, NO_2^-- and NH_4^+-concentrations were measured from the wet deposition samples.

Plant coverage and composition of species

At the AB and AF sites the total coverage and the composition of the most dominant plant species were recorded from the sub plots in early August 2003 (Table 2).

Cellulose decomposition

The cellulose decomposition test was carried out during three periods; from June 6 to September 11 2003, from October 15 2003 to May 7 2004 and from May 7 to September 15 2004 in the AB and AF sites. Pieces of cellulose (5 cm × 10 cm) were dried at 105°C, stabilized for 2 h at room temperature and weighed. Three pieces were inserted in a plastic net (mesh size 1 mm) and buried in the peat on each site at depths of 0–5, 5–10 and 10–15 cm. After the in situ incubation period the ingrown roots and mosses were cleaned off, and the pieces were dried and weighed at the same way as before installation. The cellulose decomposability was calculated from the weight loss.

N_2O flux measurements

Gas fluxes were measured throughout 2 or 3 years every second or third week (Figs. 1a, b, 2). During the snow free periods, fluxes of N_2O were measured with a static chamber method (Nykänen et al. 1995). Permanent aluminium frames (58 × 58 cm) and an aluminium chamber (60 × 60 cm, height 30 cm, equipped with a fan) were used at AF and AB sites. The frame had a groove in the upper edge which was filled with water to obtain gas tightness. Gas samples (40 ml) were drawn from the headspace of the chambers with 60 ml polypropylene syringes (Terumo or Becton-Dickinson) equipped with a three-way stopcock 5, 10, 15 and 25 min after the chambers were installed. Gas concentrations were analysed within 24 h from sampling with gas chromatographs (Shimadzu GC-14B or Hewlett-Packard 5890) equipped with electron capture (EC) detectors (Nykänen et al. 1995; Maljanen et al. 2003a). Gas flux measurements at AFC sites were made with a galvanized steel cylinder (height 30 cm, diameter 31.5 cm). Samples were taken at 5, 15, 25 and 35 min intervals as described above and were stored in pre evacuated 12 ml glass vials (Excetainer Labco Inc.) for analysis with Hewlett-Packard 6890 gas chromatograph equipped with EC-detector (Regina et al. 2004). Standards of 0.389 and 3.0 μl l^{-1} N_2O were used for hourly calibration of EC. The number of sub plots (= sampling plots with permanent frames and chambers or with cylinders) from each site are shown in Table 3. The N_2O flux rates were calculated from the linear change in the gas concentrations in the headspace of the chamber. During winter the N_2O fluxes were determined by a gas gradient technique (Maljanen et al. 2003b; Sommerfeld et al. 1993). Gas samples for concentration analyses of N_2O were drawn from the snow pack using a stainless steel probe, diameter 3 mm. This method is comparable to the chamber method in conditions with homogenous and non-disturbed snow pack (Maljanen et al. 2003b; Alm et al. 1999) and these conditions were always fulfilled during the snow gradient sampling. Annual emissions were calculated for each sub plot separately using time weighted average values of measured emissions.

In situ net nitrification

Net nitrification in situ was measured with intact soil cores (PVC tubes, diameter 7.4 cm, height 20 cm). Measurements were made in sites AF1, AF5, AB4 and AB5. The walls of the PVC tubes had small holes (diameter 3 mm), which were sealed with a polyethylene film. The sealed holes allowed lateral movement of soil gases, but water movement was hindered when the cores were placed back to soil for

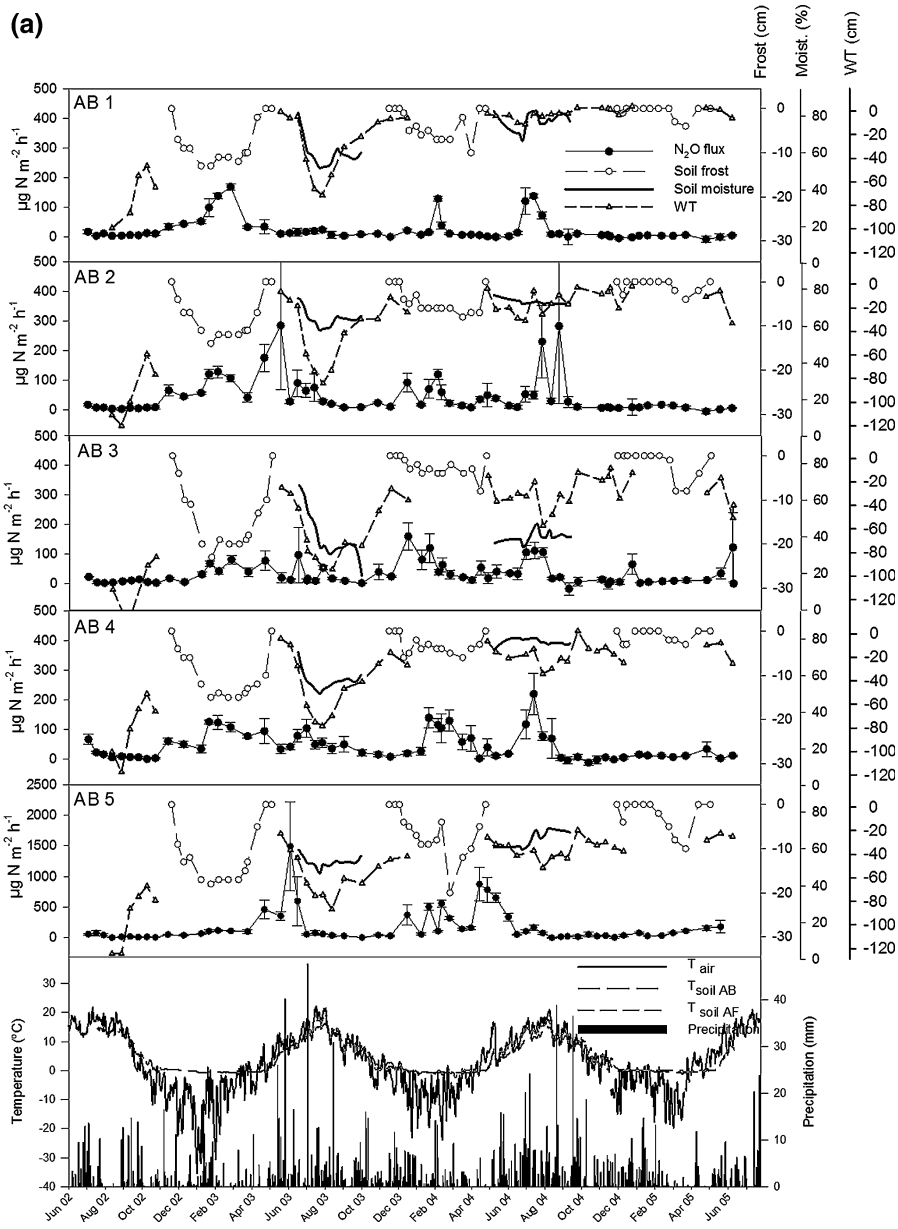


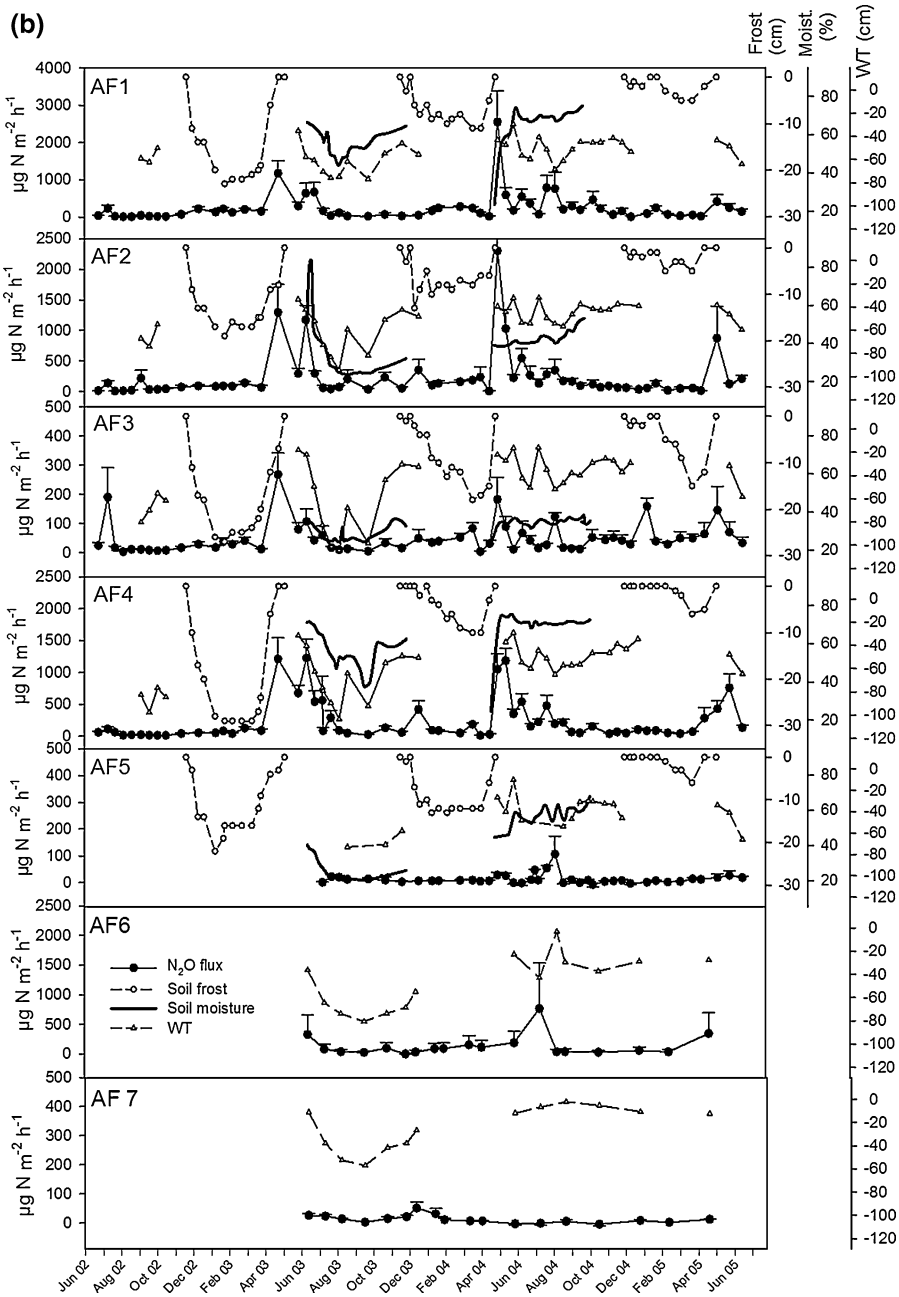
Fig. 1 **a** N_2O flux dynamics (*black circle*) on abandoned sites AB1–AB5 shown with soil moisture (*solid line*), depth of soil frost (*open circles*) and ground water table level (*triangles up*). Note different scale in AB5 site for N_2O flux rates. Mean daily air temperature, soil temperature from site AB3 at depth of 5 cm and daily precipitation are shown at the bottom. **b** N_2O flux dynamics (*black circle*) on afforested sites AF1–AF7 shown with soil moisture (*solid line*), depth of soil frost (*open circles*) and ground water table level (WT) (*triangles up*). Note different scales for N_2O flux rates

incubation in situ. The upper end of the core was covered with an aluminum foil. After incubation period (from October 13, 2004 to May 25, 2005) the cores were removed from the field. Concentrations of NO_3^- and NH_4^+ were determined from the pooled soils (extraction with H_2O and 1 M KCl) sampled close to the cores in the beginning of the incubation period and from pooled soil samples inside the cores in the end of the incubation period. The amount of NO_3^- and NH_4^+ in the soil extracts were analyzed as described earlier.

DNDC model

The DNDC (DeNitrification–DeComposition) model is a process oriented model of soil carbon and nitrogen biogeochemistry, widely used in temperate and tropical conditions (Li et al. 2004, 2006). We

Fig. 1 continued



evaluated this model to investigate if this model can explain the wide differences in the land use change associated GHG exchange patterns among sites using the daily time series of air temperature, solar radiation and rainfall data as the main model drivers from the Kannus region for the period from 2002 to 2005. For the purpose, we selected two sites with contrasting N_2O emission characteristics. The abandoned site (AB1) treated as a grassland (low N_2O emitting) and the site afforested with birch (AF1, high N_2O emitting) were selected for model simulations. Soil characteristics from these two sites (Table 1), were used as model inputs. These values and other information related to land use history are described above. The model has three different input modules: climate, soil and management. The various

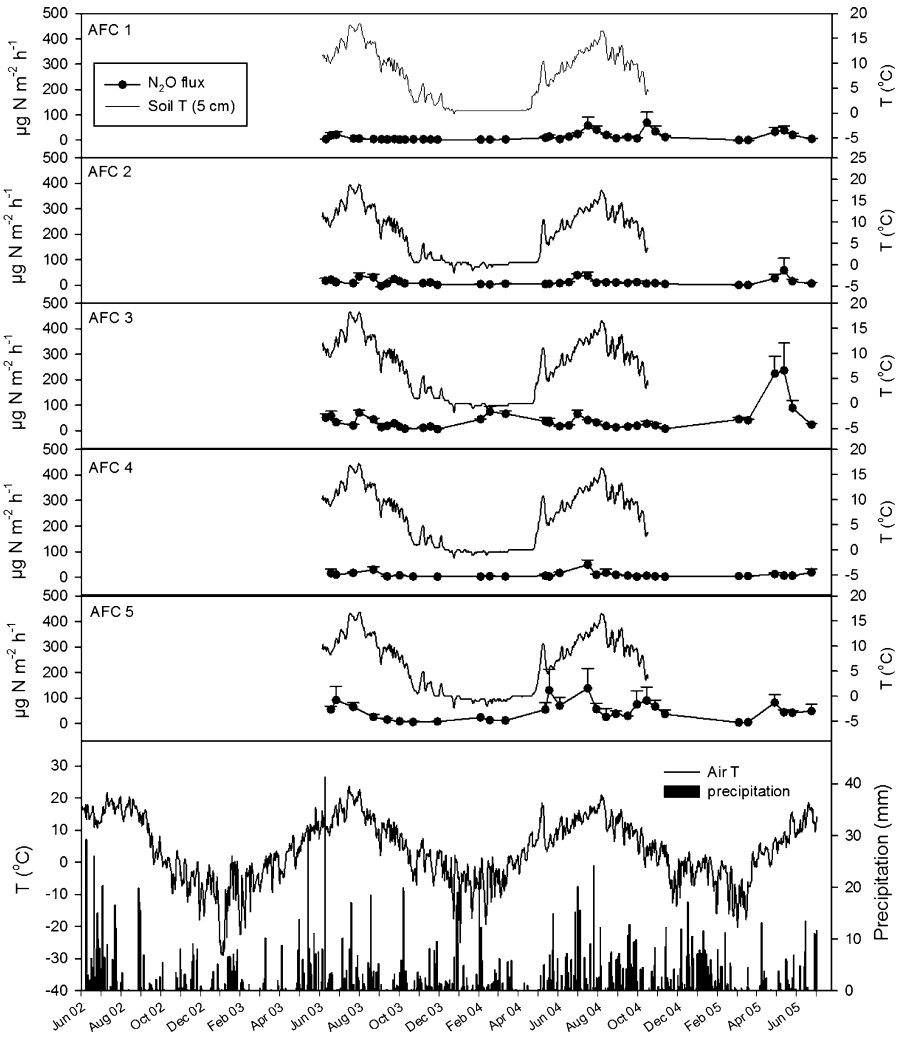


Fig. 2 N_2O flux dynamics (*black circle*) on afforested peat extraction sites AFC1–AFC5 shown with soil temperature at 5 cm (*solid line*). At the bottom: mean daily air temperature and daily precipitation from the nearby (30 km) weather station

details in the three input modules were furnished to best represent the grassland and afforestation practices on an organic soil under Finnish conditions.

Statistical methods

Relationships between environmental variables and annual N_2O emission rates were studied with correlation analysis (Pearson correlation or Spearman Rank correlation if the variables were not normally distributed) and principal component analysis (PCA) SPSS 14.0. Differences in the environmental variables between sites were studied with one way ANOVA and Tukey's test. Linear regression was used to illustrate relationship between N_2O emissions and WT level (SPSS 14.0).

Results

Weather conditions and soil temperature

The 2002 summer was warm, with a maximum temperature of 28°C measured in July 2002. The following winter was cold, the lowest measured air temperature was −40°C in the end of December 2002 (Fig. 1a). During the first measuring period, from July 2002 to June 2003, the annual precipitation in Kannus and Kihniö was less than the long term average (LTA), the second period, from July 2003 to June 2004, was drier in Kihniö but wetter in Kannus. During the last period, from July 2004 to June 2005, the annual precipitation was higher than the LTA at both sites (Table 4).

Table 3 Annual N_2O emissions (average from replicate sub plots ± sd, kg N ha^{-1}) from 3 years (from July 1 to June 30), the mean emission from all years with the proportion (W%) of winter (from October 1 to April 30) of the annual emissions and the NO_3^- and NH_4^+ (μg N g^{-1}) concentration measured from the depth of 0–20 cm

Site name	Sub plots	2002–2003 annual N_2O emission (kg N ha^{-1})	2003–2004 annual N_2O emission (kg N ha^{-1})	2004–2005 annual N_2O emission (kg N ha^{-1})	Mean annual N_2O emission (kg N ha^{-1})	W (%)	Mean[b] NO_3 (μg N g^{-1})	Mean[b] NH_4^+ (μg N g^{-1})	Mean WT (cm)	CD (%)
Afforested agricultural soils										
AF1	4	21.9 ± 8.3	24.4 ± 9.5	19.7 ± 3.1	22.0	46	77.4	10.7	−54	69.7
AF2	4	23.5 ± 8.4	26.1 ± 8.6	14.7 ± 4.9	21.4	42	66.6	13.3	−52	60.8
AF3	8	5.0 ± 3.5	3.7 ± 2.5	5.2 ± 4.2	4.7	58	11.1	20.1	−47	70.1
AF4	8	22.5 ± 11.8	20.7 ± 8.9	16.7 ± .6.4	20.0	33	36.9	10.1	−59	57.1
AF5	4	nd	1.0 ± 0.4	1.2 ± 0.6	1.1	49	5.9	14.0	−41	41.4
AF6	5	nd	11.1 ± 4.5	11.9 ± 7.7	11.5	51	15.5	21.7	−47	nd
AF7	5	nd	1.15 ± 0.8	0.2 ± 0.6	0.7	41	7.0	27.0	−25	nd
Abandoned agricultural soils										
AB1	4	3.4 ± 0.6	1.8 ± 0.4	1.0 ± 0.3	2.1	45	3.2	34.8	−21	25.2
AB2	4	6.3 ± 2.0	3.3 ± 1.0	2.7 ± 1.7	4.1	47	11.5	12.8	−35	23.7
AB3	4	2.8 ± 1.3	4.4 ± 1.2	2.0 ± 0.7	3.1	51	15.6	8.4	−50	49.2
AB4	4	4.7 ± 0.2	5.4 ± 2.8	2.1 ± 1.2	4.1	46	19.3	19.7	−35	22.0
AB5	4	15.6 ± 9.2	20.2 ± 3.2	6.9 ± 1.9	14.2	54	20.7	11.8	−51	75.5
Afforested peat extraction sites										
AFC1	8	nd	0.6 ± 0.5	1.7 ± 2.0	1.1	16[a]	0.63	36.9	−65	nd
AFC2	4	nd	1.0 ± 0.4	1.1 ± 0.6	1.0	26[a]	2.81	73.0	−84	nd
AFC3	4	nd	2.6 ± 1.3	6.1 ± 2.2	4.3	48[a]	36.5	24.5	−78	nd
AFC4	2	nd	1.0 ± 0.5	0.6 ± 0.5	0.8	20[a]	<0.1	9.81	−74	nd
AFC5	2	nd	4.1 ± 2.6	5.4 ± 1.5	4.8	31[a]	3.5	22.5	−72	nd

Mean WT is the average water table level below the soil surface during the growing seasons. Cellulose decomposition (CD) was measured from AF and AB plots in 2004

[a] Winter emissions only from one winter

[b] AB and AF sites were sampled annually in June and in September, AFC sites once in 2005

Table 4 The mean annual temperatures (from July 1 to June 30) in Kannus (AF and AB sites) and in Kihniö (AFC sites)

Season	Kannus (AF and AB sites)				Kihniö (AFC sites)			
	Mean T	Δ	Annual Precipitation	Δ	Mean T	Δ	Annual precipitation	Δ
1. 2002–2003	0.9	−1.5	534	−27	2.4	−0.7	542	−112
2. 2003–2004	2.8	0.4	730	169	4.2	1.1	530	−124
3. 2004–2005	3.8	1.4	705	144	4.1	1.0	665	11

Δ = difference from the long term average values (1971–2000) (Drebs et al. 2002)

In 2002, the soil frost started to develop in late November in the AF and AB sites but later in the following years. The maximum depth of soil frost, 29 cm, was detected from the site AF4 (Fig. 1b) in 2003. The two following winters were milder than the first one, the maximum soil frost depth in the AF and AB sites varied from 4 to 17 cm. Soils thawed during the period from late April to early May. Soil frost was not measured at the AFC sites.

The maximum measured soil temperatures in the AB and AF sites at the depth of 5 cm was 19.6°C in July 2003 and the minimum was −2.4°C in March

2004. During winter, soil temperatures remained close to 0°C in all sites (Figs. 1a, 2).

The water table depth (WT) in the AB sites varied between 154 cm below soil surface to 5 cm above the soil surface, being on the average 46 cm below the soil surface from May to October (Figs. 1a, b, 2; Table 2). In the AF sites the mean WT depth was 50 cm and ranged from 117 cm below soil surface to 10 cm above soil surface from May to October. In the AFC sites WT ranged from >101 to 17 cm below the soil surface. In these sites WT level was occasionally lower than the water wells (101 cm) and could not be measured. During the growing seasons of 2002 and 2003 WT remained deeper than that during the growing season 2004 in all sites.

During the growing season 2003, pH in the wet deposition collected from the AB sites varied from 5.1 to 5.3, electrical conductivity from 6.2 to 6.6 μS cm^{-1}, and the amount of N (NO_2-N + NO_3-N + NH_4^+-N) from 0.66 to 0.77 kg N ha^{-1}. The highest amount of N in the wet deposition was measured from the site AB5, however, there were no statistical differences in the N-deposition rates between the sites.

N_2O flux dynamics

N_2O flux dynamics in abandoned and afforested agricultural soils

N_2O emission rates varied largely between the sites and seasons. From August 2002 until November 2002 with unfrozen topsoil, all sites (AF1, AF2, AF3, AF4, AB1, AB2, AB3, AB4 and AB5) emitted less than 100 μg N_2O-N m^{-2} h^{-1}. From November 2002 to the late Mach 2003 when the soils remained frozen, the N_2O emissions from each site were higher (Fig. 1a, b). From early April 2003 up to July 2003 high amounts of N_2O was emitted from the thawing soil (up to 2,500 μg N_2O-N m^{-2} h^{-1}). Site AB1 was an exception. There the N_2O emission decreased during that time. During the second summer, 2003, the high emissions decreased towards autumn remaining low until the topsoil was frozen again in December 2003. During the second winter, all sites, except the new afforested site AF5, had high N_2O emissions. As in 2003, there was a period with high N_2O emissions immediately after soil thawing in April 2004. Heavy rain events also increased N_2O emissions at some sites during the summer 2004. However, sites AF7, AB1 and AB2 showed N_2O uptake (up to 77 μg N_2O-N m^{-2} h^{-1}), when the water table level was high. In the autumn 2004, N_2O emission rates decreased again remaining at a low level also after soil freezing in December. In the spring 2005, during thawing, there were no thawing related N_2O peaks at the AB1, AB2 AB4, AB5 and AF7 sites in contrast to previous years, but in other sites small thawing peaks were seen.

There were no straightforward correlations with the depth of soil frost and the N_2O emissions rates. However, in early winter, N_2O emissions increased with soil frost development but on the other hand, high N_2O emissions occurred also at soil thawing in spring. Also the effect of soil temperature on the N_2O emissions was not clear. Soil temperature at the depth of 5 cm correlated negatively with the N_2O emission at the sites AF3, AB3 and AB5 ($p = 0.005$; $p = 0.021$; $p < 0.001$) but positively at the sites AF4, AF5, AFC1, AFC2, AFC4 and AFC5 ($p = 0.36$; $p < 0.001$; $p < 0.001$; $p < 0.001$; $p = 0.004$; $p = 0.024$). There was a different optimum temperature for N_2O emissions during the growing season and the winter at each site. During the growing season the highest emissions occurred when soil temperature at the depth of 5 cm was between 10 and 12°C and in the winter between −1 to +2°C (Fig. 3).

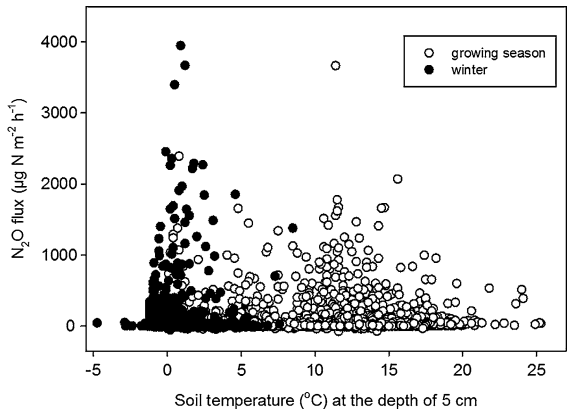


Fig. 3 All measured N_2O fluxes from individual subplots plotted against soil temperature at depth of 5 cm. Measurements during the growing season (from 15 May to 30 September) are shown with *open circles* and winter (the rest of the year) with *black circles*

N_2O flux dynamics in afforested peat extraction sites

Measurements at the afforested peat extraction sites started in June 2003 when all sites emitted N_2O. Emissions then decreased during the autumn 2003. Two of the sites (AFC3 and AFC5) showed very low N_2O emissions during the winter. During soil thawing in spring 2004 enhanced emissions were seen only at the site AFC5. The thawing peak in other sites was probably missed due to a low measuring frequency. During the summer 2004 all AFC sites emitted N_2O and emissions decreased in the autumn similarly as in 2003. The highest emissions took place at the site AFC5 associated with an increase in air temperature in early May 2004. During the second winter, emissions were not measured between December–February 2005. In May 2005, emissions during soil thawing were high, especially at site AFC3.

Factors behind annual N_2O emissions

Annual N_2O losses

There was a high variation between sites and years (Table 3), the annual N_2O emissions from individual sub plots varied from −0.50 to 46.1 kg N ha^{-1}. The emissions were highest from the four AF sites and from an AB site (Table 3). On average, all sites had net N_2O emissions on annual basis, even though some sub plots at sites AB1, AB2, AB3, AB4 and AF7 showed occasionally N_2O uptake. These sub plots with N_2O uptake, were wet, occasionally the WT level was close to the soil surface and even 10 cm above it. These plots at site AF7, were located on the bottom of a furrow but those at AB sites were located on more even surfaces, which were flooded during the wet periods.

The average annual emissions with standard deviations from AF sites were 12.8 ± 9.4 kg N_2O-N ha^{-1}, from the AB sites 5.5 ± 5.4 kg N_2O-N ha^{-1} and from AFC sites 2.4 ± 2.1 kg N_2O-N ha^{-1}. Emissions outside growing season contributed significantly to the annual emissions. In AF sites these emissions were on average 46% of the annual, in AB sites 49% and in AFC sites 28%, respectively (Table 3). In AF and AB sites the relative proportion of winter time emissions was not connected to the magnitude of annual emission, whereas in AFC sites the proportion of winter emissions were higher in sites with higher annual emissions (AFC3 and AFC5).

Water table level

The weather conditions varied widely among the years. The late summer 2002 was very dry and warm, the following summer 2003 was rainy and the summer 2004 was very wet. Therefore, WT was at the deepest level in year 2002 and the shallowest in year 2004. Within most of the AB and AF sites there was a negative correlation with N_2O emissions and the mean WT level depth between the years (Fig. 4). Mean annual N_2O emissions decreased with increasing mean WT level depth (range 0–50 cm) at sites AF1, AF2, AF4, AB1, AB2 and AB4. Exception of this trend were sites AB5 and AB3 emissions were at the highest during the second year but lower in the driest and wettest year. AFC sites had all lower mean WT level (<60 cm) than the AB and AF sites and they had also lower N_2O fluxes. This indicates that the N_2O fluxes do not increase continuously with the lowering of WT—when WT falls below a critical level (between 50 and 70 cm) the N_2O emissions decrease (Fig. 4).

Vegetation

The time period since the cultivation practices ended or the age of tree stands did not correlate with the annual N_2O emissions. Neither did the tree species (deciduous or coniferous) have any significant effects on the annual N_2O emissions at the AF or AFC sites. The average annual emission of the three study years were 8.6 ± 7.3 kg N ha^{-1} from the coniferous sites (pine) and 10.0 ± 11.2 kg N ha^{-1} from the deciduous sites (birch).

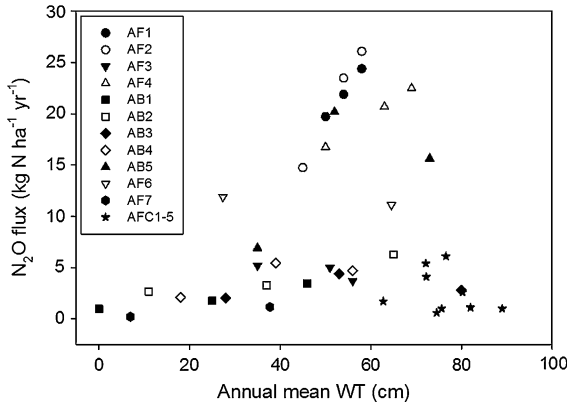


Fig. 4 Annual N_2O emissions plotted against annual mean water table level (WT as a positive value) in AF, AB and AFC sites

Soil physical and chemical properties

Soil bulk density, peat depth, OM, pH, K, P or NH_4^+ content or soil T did not explain the differences in the annual N_2O emissions between the sites (Fig. 5). Soil NO_3^- concentration, however, had significant positive correlation with the mean annual N_2O emission ($F = 45.2$, $p < 0.001$). This relationship was best described with a single rectangular hyperbola equation (see Fig. 5).

Annual N_2O emissions and soil C:N ratio did not have any straightforward correlation. When the mean annual N_2O emissions from all sites were plotted against the C:N ratio of the soil organic matter

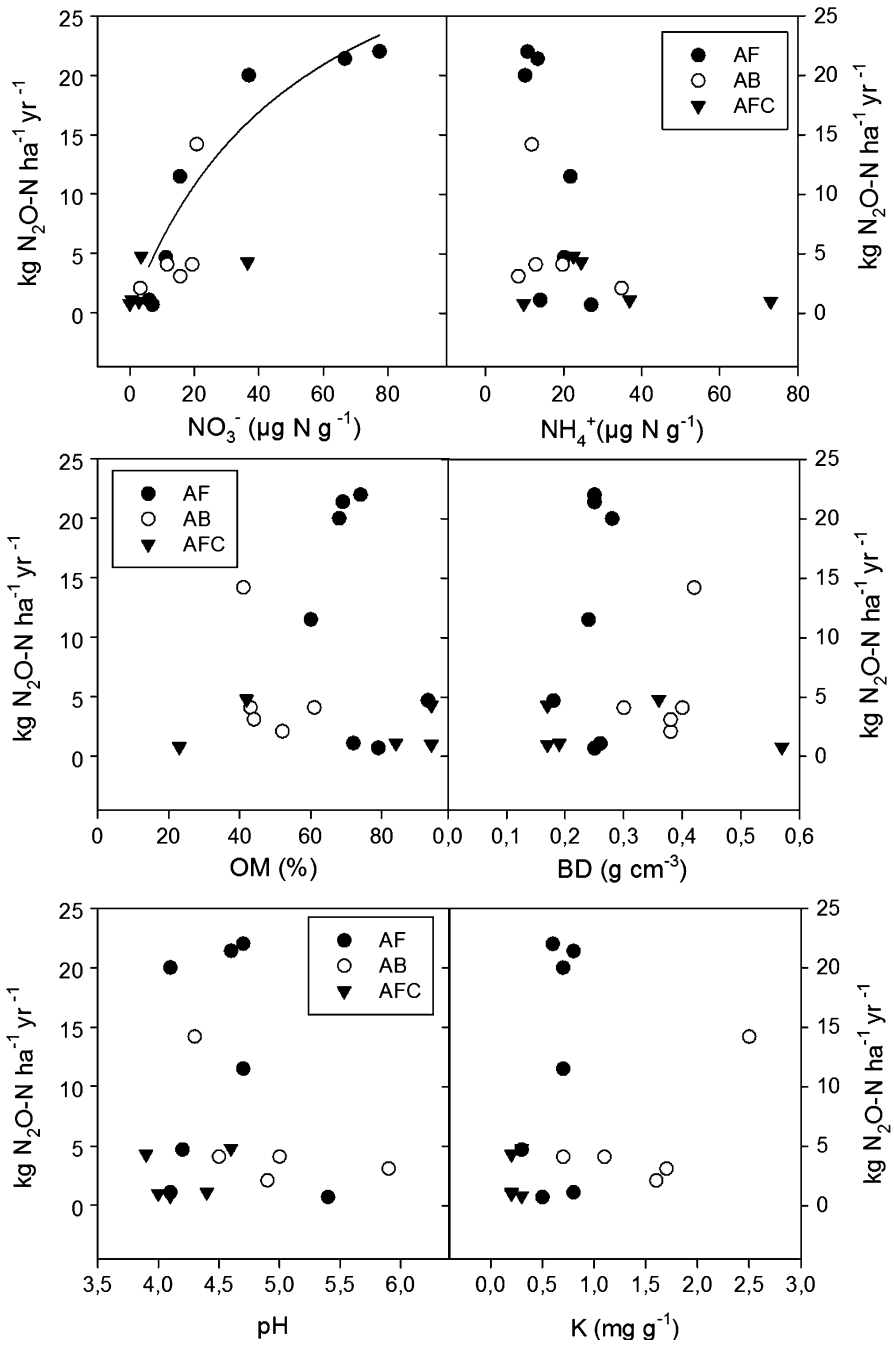


Fig. 5 Soil physical and chemical properties plotted with annual N_2O emissions from afforested croplands (AF), abandoned croplands (AB) and afforested peat extraction sites (AFC). A significant correlation with soil NO_3^- concentration with N_2O emission was the form of rectangular hyperbola equation ($f = a*x/(b + x)$, $R^2 = 0.75$)

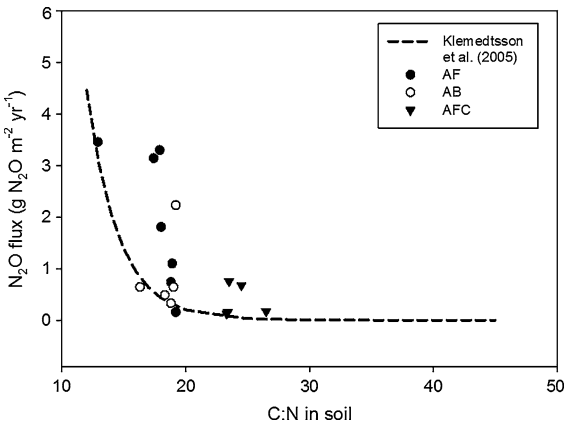


Fig. 6 Annual N_2O emission rates plotted against soil C:N ratio and with the curve presented by Klemedtsson et al. (2005)

presented by Klemedtsson et al. (2005) most of our former agricultural sites and two peat extraction sites had much higher emissions than the C:N ratio would predict (Fig. 6). With soil C:N ratio below about 20 both very high and very low emissions may occur.

In the AB and AF sites cellulose decomposition rate did not correlate with the N_2O emissions during the growing seasons. However, PCA analysis (Fig. 7) revealed that N_2O emissions had some association with the cellulose decomposition rates, soil NO_3^- and K-concentration and soil moisture (WT level). Soil pH, temperature, total plant coverage, soil P, Ca, Mg or NH_4^+-concentration did not have any straightforward correlation with annual N_2O emission rates.

In situ net nitrification

Net nitrification rates in situ (NIT) measured from the AF1, AF7, AB4 and AB5 sites correlated with the annual N_2O emissions (Fig. 8). The NIT rates were the lowest at the AB4 and AF7 sites, which had also low N_2O emission rates. The highest NIT rate (6.95 mg N m^{-2}) took place at the AF1 site showing also the highest N_2O emission. The relationship between the NIT and the N_2O emissions was explained best with an exponential function: annual N_2O flux (mg N m^{-2}) = 98.84 + 39.31 * exp (0.57 * NIT), $R^2 = 0.97$.

Modelling of N_2O emissions with DNDC

The comparison of the DNDC simulated and measured N_2O and CO_2 emissions from an abandoned site (AB1) and an afforested site (AF1) are presented in Figs. 9 and 10. For the AB1 site, the DNDC simulated ecosystem respiration was compared with the diurnal ecosystem respiration reconstructed from the measured data (M. Maljanen unpublished data). The ecosystem respiration includes heterotrophic, root and aboveground dark respiration components. For the afforested site (AF1), modeled ground CO_2 emissions were compared with the measured ground respiration rates (data from P. Mäkiranta, Finnish Forest Research Institute). The ground respiration includes heterotrophic, root and litter respiration.

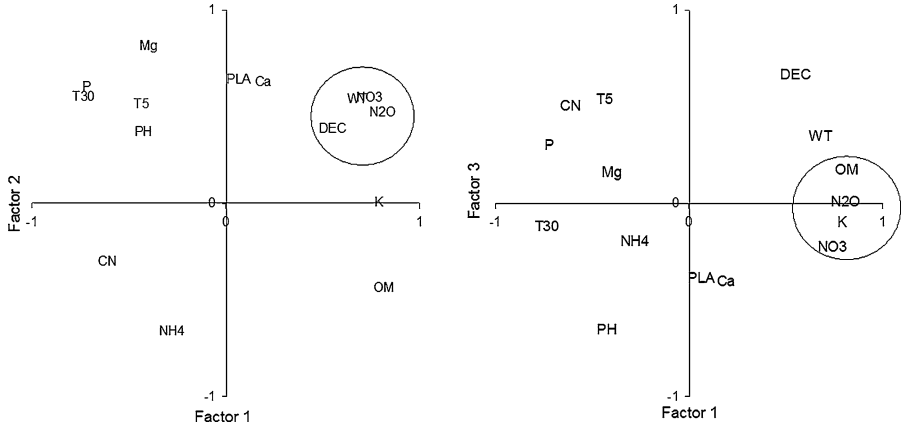


Fig. 7 Principal component analysis (PCA) of environmental variables (*WT* water table; *T5*, *T30* soil temperatures at depth of 5 and 30 cm; *K*, *Ca*, *Mg* soil K, Ca, Mg content; *C/N* soil C/N ratio; *pH* soil pH (H_2O); *PLA* total plant coverage; *OM* organic matter content; *DEC* cellulose decomposition ability; *NO_3*, *NH_4* soil nitrate and ammonium content) and annual N_2O emissions (N_2O). *Factors 1* and *2* explain 63.6% of the variance and together with *factor 3*. 77.6% of the variance is explained. Variables in the *circles* are closely connected to N_2O emissions

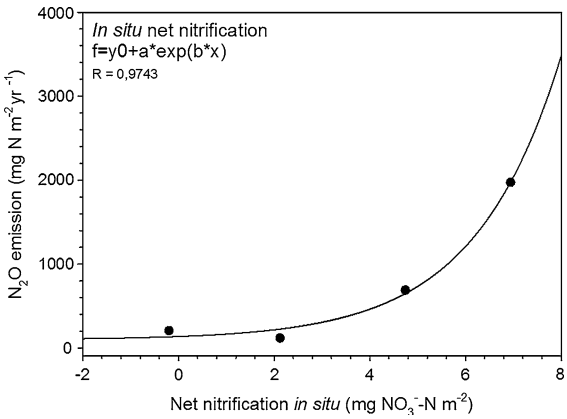


Fig. 8 Net in situ nitrification rate in two afforested sites (AF1 and AF7) and two abandoned cropland sites (AB4 and AB5) plotted with in situ N_2O emission rate

For both sites, modeled daily N_2O emission rates are compared with instantaneous measured values.

There was a reasonably good agreement between the measured and modeled respiration rates at both sites (Figs. 9, 10). A linear regression between the modeled and measured CO_2 emission rates from the afforested site during 2003 and 2004 yielded adjusted R^2 values of 0.92 and 0.93, respectively ($p < 0.001$). The slopes of the 1:1 line for 2003 and 2004 were 1.2 and 0.79, respectively implying that the modeled values, on an average, overestimated respiration in 2003 by 20% and underestimated it by 19% in 2004. A similar analysis of the modeled and observed ecosystem respiration data from the grassland site in 2003 resulted in an adjusted R^2 value of 0.85 with a 1:1 line slope of 1.38 (data from P. Mäkiranta, Finnish Forest Research Institute). The simulated annual N_2O emissions were of the similar magnitude as the measured values. However, a closer look at the emission patterns within a given year revealed that the simulated N_2O emissions were close to zero beyond the growing season at both the sites. Also, while the measured data indicate high N_2O emissions associated with snow melting during spring particularly at the AF1 site, the simulated values show a minimal N_2O release during this time. Modeled values indicated a seasonal trend with high emissions during the middle of the growing season when the temperature was high. Superimposed on the gradual

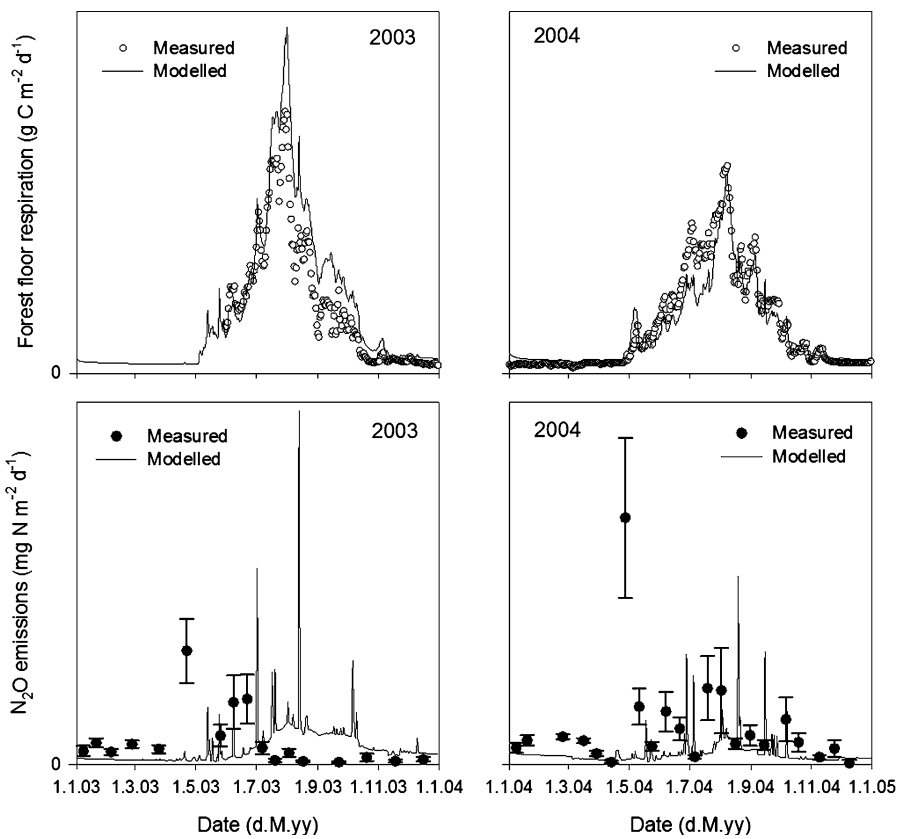


Fig. 9 Modelled (*solid line*) and measured (*open circles*) CO_2 (forest floor respiration) and N_2O emissions from an afforested cropland (site AF1) during years 2003 and 2004. CO_2 data from P. Mäkiranta (Finish Forest Research Institute 2008)

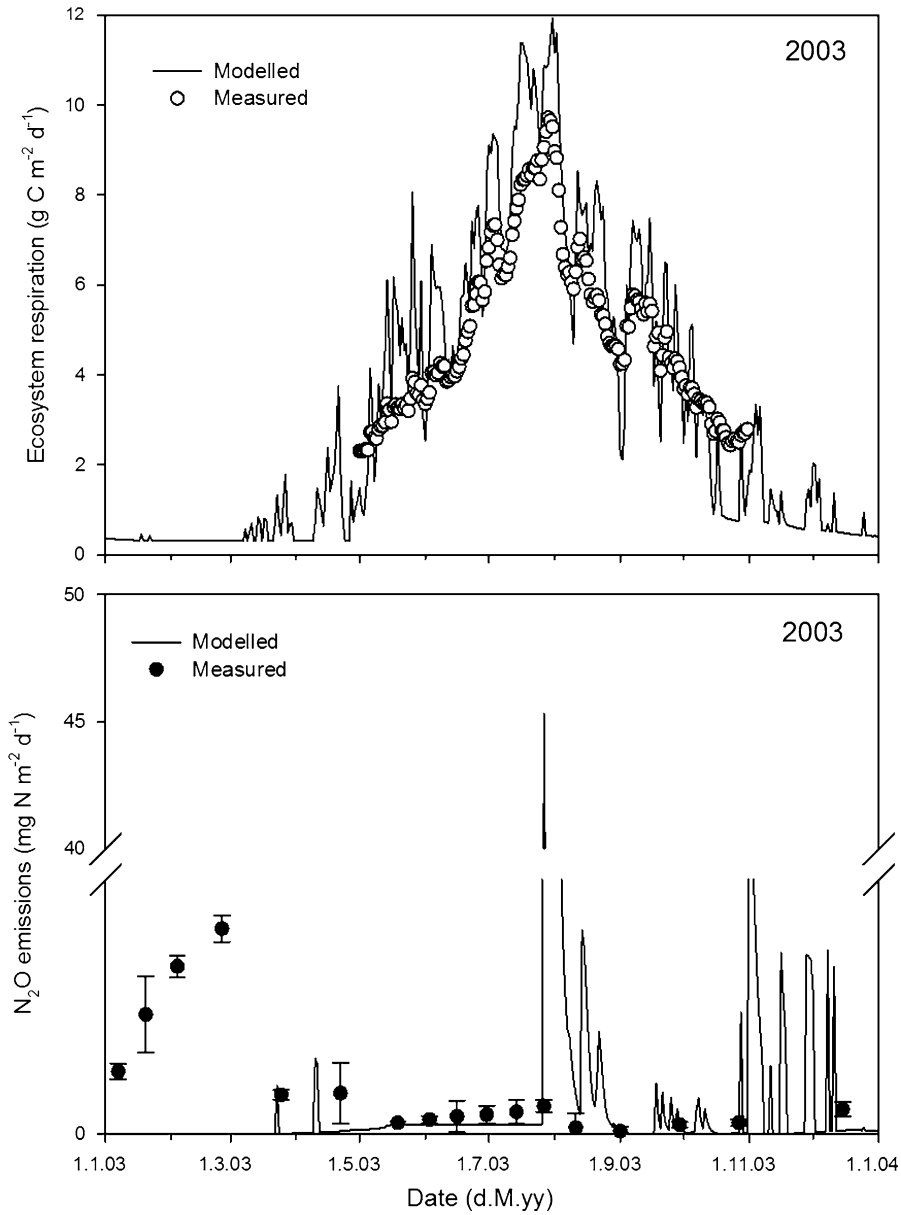


Fig. 10 Modelled (*solid line*) and measured CO_2, ecosystem respiration (*open circles*) and N_2O emissions (*black circles*) from an abandoned cropland (site AB1) during year 2003. Measured CO_2 data from M. Maljanen (unpublished)

seasonal pattern were episodic N_2O emissions associated with heavy rain events during the season.

Discussion

The N_2O emissions from the 17 sites studied here had great spatial and temporal variation. The N_2O fluxes varied with uptake rates as high as 77 μg N_2O-N m^{-2} h^{-1} emissions, 4,000 μg N_2O-N m^{-2} h^{-1}. In this paper, we report only the estimates of annual emissions using data measured with manual chambers at a 2–3 week sampling intervals. Thus, some peak emissions events (e.g. freeze–thaw events, rainfalls, e.g. Maljanen et al. 2009) may have been missed. Within the resources available intensive campaigns during the potential peak events were not planned for the numerous sites of the study.

High N_2O uptake rates (up to 77 μg N m^{-2} h^{-1}) were measured when peat had high water content during flooding in the growing season 2004. These uptake rates are in the range reported for several ecosystems, including peat soils (Chapuis-Lardy et al. 2007). Although the N content in peat is high (from 1.0 to 2.6%) the NO_3^- concentration in peat porewater is generally low at high soil water content. In these conditions N_2O in soil can act as an electron acceptor and is reduced to N_2 in denitrification (Frasier et al. 2010; Chapuis-Lardy et al. 2007). Then the N_2O concentration in soil drops and N_2O can even be transferred from the atmosphere into the soil.

Afforestation of abandoned agricultural peat soils did not reduce N_2O emissions. Mean annual N_2O emissions from the afforested agricultural soils (12.8 ± 9.4 kg N ha^{-1}) were much higher than those measured with similar methods from nutrient rich peat soils drained for forestry, 2.3 ± 3.0 kg N ha^{-1} (Martikainen et al. 1993; Huttunen et al. 2003; Maljanen et al. 2003a, 2006), but they were similar to the mean annual emissions from organic agricultural soils in active use in Finland, 11.8 ± 8.8 kg N ha^{-1} (Nykänen et al. 1995; Regina et al. 1996, 2004; Maljanen et al. 2003a, 2004, 2009) and in Sweden (from 1.3 to 9.6 kg N ha^{-1}, Kasimir Klemedtsson et al. 2009). N_2O emissions from afforested agricultural sites were also higher than the emissions (range from 0.2 to 5.8 kg N ha^{-1}) reported recently from 68 peatlands drained for forestry in Finland (Ojanen et al. 2010). The mean annual emission from afforested peat extraction sites (2.4 ± 2.1 kg N ha^{-1}) was higher than those from Finnish peat sites under active extraction, from 0.03 to 2.0 kg N ha^{-1} (Alm et al. 2007; Hyvönen et al. 2009; Nykänen et al. 1996). However, the mean emissions (5.5 ± 5.4 kg N ha^{-1}) from abandoned agricultural soils (without afforestation) were lower than those from agricultural soils in active use (11.8 ± 8.8 kg N ha^{-1}).

The difference in the N_2O emissions between the sites and the land-use options cannot be explained well with the environmental variables available. The abandoned agricultural soils, without N-fertilization, have still a considerable N-pool bound in the organic matter (peat). When mineralized and nitrified this nitrogen pool provides plenty of NO_3^- for denitrification which is probably the main source of N_2O from drained organic agricultural soils (Maljanen et al. 2003a). In situ nitrification measurements confirm that nitrification is an important controlling factor for the N_2O production in these drained organic soils.

In addition to nitrate, soil moisture was also a factor connected to the N_2O emissions (PCA analysis). Water table level explained the N_2O dynamics within one site, but not well among various sites with slightly different land use history or soil properties. In most of the sites the annual N_2O emissions increased with decreasing annual mean WT level in the range from 0 to 60 cm. In the AB5 and AB3 sites the lowest emissions took place during the driest and wettest years. This indicates that if the soil moisture is low enough, WT level lower than 70 cm, the N_2O production is limited. With high moisture either the low availability of nitrate and/or efficient reduction of N_2O to N_2 decrease the N_2O emission. As indicated in Fig. 4, the optimum WT level for the N_2O emission could be between 50 and 70 cm in the AF and AB sites and about 75 cm in the AFC sites. Therefore, keeping the WT level close to the soil surface could be an option to mitigate N_2O emissions from drained peat soils. However, elevation of WT level may result to the increase in methane emissions (e.g. Yli-Petäys et al. 2007). The lowering of the water table below 80 cm is not a proper option to reduce the N_2O emissions because the low WT increases penetration of atmospheric oxygen into the peat and enhances the decomposition of peat (CO_2 emissions).

Average pH in the afforested soils was 4.4 which is lower than that in agricultural peat soils regularly fertilized and limed (e.g. Maljanen et al. 2003a, 2004; Regina et al. 2004). In soils, a variable part of the produced N_2O is reduced to N_2. The N_2O reductase enzyme is inhibited at a low pH (Richardson et al. 2009). In the abandoned but not forested sites, mean soil pH was slightly higher (4.9) than in the afforested soils and there the N_2O emissions were lower than those from the afforested agricultural soils. The high N_2O emissions from the afforested sites could thus be related to the low soil pH and limited reduction of N_2O as reported also by Weslien et al. (2009).

Organic matter (OM) content did not explain the N_2O emissions, very low emissions were measured from the AF5 site with similar OM content than in other soils showing higher emissions. Klemedtsson et al. (2005) and Ernfors et al. (2007) reported that the C:N ratio of organic forest soils can be used as a scalar to up-scale the N_2O emissions. The low C:N ratio evidently reflects high availability of mineral

nitrogen for microbial processes. The low C:N ratio, less than 20, favours also here the N_2O emissions. However, high variability in emissions led to poor relationship with the C:N ratio. In agricultural soils, other factors such as fertilization and ploughing may overcome the C:N dependence. An additional mixing factor could be the mineral soil added to improve properties of peat for plant growth (Wall and Hytönen 1996; Hytönen et al. 2008). Only one of the afforested agricultural soils was left without mineral soil addition (AF3). This site had also lower N_2O emissions than the closest sites (AF1, AF2 and AF4) with mineral soil treatment. This untreated site (AF3) also fits better to the C:N curve of Klemedtsson et al. (2005) than the treated sites (AF2, AF4 and AFC5), see Fig. 7. This suggests that the mixing of mineral soil with peat could increase N_2O emissions.

Four of the abandoned sites had rather similar annual N_2O emissions. The site AB5, with high emissions, was located close to a fur farm. The long lasting extra nitrogen deposition from the farm could result in a higher nitrate availability in soil and thus higher N_2O emissions (Kitzler et al. 2006). However, the measured N-deposition during years 2003–2004 was not statistically higher in AB5 than in the other AB sites.

This study confirms the importance of winter in the annual N_2O budget. Winter emissions (those outside the growing season) were on average 40% of the annual N_2O emissions, at some sites even more than 70%. Therefore, winter emissions have to be included in the annual estimates of N_2O emissions from drained boreal peat soils. The high N_2O emissions in early winter were associated with soil frost development and high emissions in spring with soil thawing. These episodic emissions were strongly dependent on soil moisture at the time of soil freezing. Therefore, these emissions varied among years depending on the frost and soil moisture conditions.

We should be able to predict by biogeochemical modelling the N_2O emissions from various soils under variable climatic conditions. We employed here the DNDC model to simulate soil climate, ecosystem/forest floor respiration (CO_2) and N_2O exchange from two experimental sites (AB and AF) showing contrasting N_2O emission patterns. We first compared the model results with the measured soil temperature, moisture and soil respiration data. The DNDC model predicted well the forest floor respiration of the afforested site and ecosystem respiration of the abandoned site. The DNDC model performance is reasonably satisfactory with respect to soil physical phenomena such as heat exchange and water movement within the soil matrix (data not shown here) and soil C loss under the environmental conditions prevailing in managed boreal ecosystems with organic soil. However, there were some instances when the modeled CO_2 values deviated significantly from the measured ones. For instance, peak emissions and emissions from mid June to mid July in 2004 at the AF site were not well simulated. For the AB site, the modeled daily ecosystem respiration values were much more variable during the growing season than the experimental data showed. The daily grassland ecosystem respiration was reconstructed using empirical transfer functions with soil temperature and/or soil moisture as the explaining variables to obtain continuous CO_2 emissions from the instantaneous measurements. It is possible that the lack of an absolute agreement between measured and simulated respiration patterns (Fig. 10) could be attributed to the low predictive power of the empirical transfer functions used in reconstructing the measured data. Having ascertained that the model performance is satisfactory with respect to soil climate and respiration data, we performed a comparison of the measured and simulated N_2O emissions.

Many recent papers have reported high N_2O emissions in winter from different northern ecosystems (e.g. Nishina et al. 2009; Maljanen et al. 2009; Goldberg et al. 2010). High emissions have been associated especially with freezing and thawing cycles (Koponen et al. 2004; Maljanen et al. 2009; Goldberg et al. 2010) but high emissions have also been reported from frozen soil (e.g. Maljanen et al. 2009). While winter emissions are a large part of the annual emissions as observed in our study sites and elsewhere, the DNDC model simulations failed to account for winter emissions. Even though the chamber measurements are not continuous and some peaks e.g. after rainfalls and freezing/thawing events may have been missed, this method indicated high emissions also during winter period, whereas the DNDC model did not. The model simulates well the summertime emissions in response to e.g. rain. The modeled results presented here hint that the model lacks proper formulations for winter N_2O dynamics in organic soils. Algorithms explaining the

production and transport of N_2O under winter conditions need to be incorporated. Thus, in order to adopt DNDC to suit the condition as they exist in boreal peat soils, the model requires structural changes at least in three major aspects: (1) redefining the soil thermal, hydraulic, redox and substrate profiles in light of the deep peat accumulations, (2) refining the anaerobic biogeochemical processes and (3) improving the gas transport processes in the peat dominated soil matrix.

Conclusion

Based on our analysis of the N_2O emission data from several years and different sites, we conclude that N_2O emissions from drained boreal organic soils can not be reduced by merely lowering their land use. Even decades after the land-use change from intensive agriculture to afforestation or abandonment without any management, N_2O emissions can still be as high as those from soils in active agricultural use. Only keeping the water level close to the soil surface could be an option to mitigate N_2O emissions in these soils. Despite a wealth of data available in this study, we could not clearly define the factors governing the N_2O exchange from these soils. Further research including field and process studies and process-oriented modelling is needed to better understand the factors and processes responsible for the high N_2O emission rates and occasional net N_2O uptake in drained boreal peat soils.

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