ISSN 0039-5471
Helsinki 2002
Suo 53(3–4): 87–96

Fluxes of nitrous oxide on natural peatlands in Vuotos, an area projected for a hydroelectric reservoir in northern Finland

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Nitrous oxide (N_2O) fluxes were measured on ten natural minerotrophic peatlands in an area planned for a hydroelectric reservoir (Vuotos) in northern Finland. The mean N_2O fluxes from the sites with mean water tables from –25 to 3.4 cm (negative below the peat surface) ranged from –30 to 230 µg m^{-2} d^{-1} during summer 1994. At the driest site, the herb-grass spruce mire with the mean water table at –38 cm, the mean summertime N_2O emission was 940 µg m^{-2} d^{-1} in 1994, attributable to the increased N_2O release at low peat temperatures in autumn. A similar increase in the N_2O emissions was not found in 1995, as the measurements were finished before the peat started to freeze. The mean N_2O fluxes at the sites correlated negatively with the mean water table levels. The peatlands in the northern boreal zone are unlikely important sources of atmospheric N_2O in their natural state. The planned reservoir would barely have large long-term N_2O emissions from the pelagic zone, but the importance of temporally flooded areas in the postflood N_2O release is uncertain similar to the short-term emissions following the flooding.

Keywords: Northern boreal peatlands, climate warming, flooding, global change, greenhouse gas emission, hydro dam

Introduction

Nitrous oxide (N_2O) is a radiatively active greenhouse gas in the atmosphere (Khalil 1999, IPCC 2001a) and it also contributes to the destruction of stratospheric ozone (Cicerone 1987). Globally, soils represent a major source of N_2O emissions to the atmosphere (Khalil 1999). Nitrous oxide is produced in soils mainly by two microbial processes, nitrification and denitrification (Davidson & Schimel 1995). Denitrification can also consume N_2O in soils (Schiller & Hastie 1994, Regina et al. 1996).

In general, natural northern wetlands have

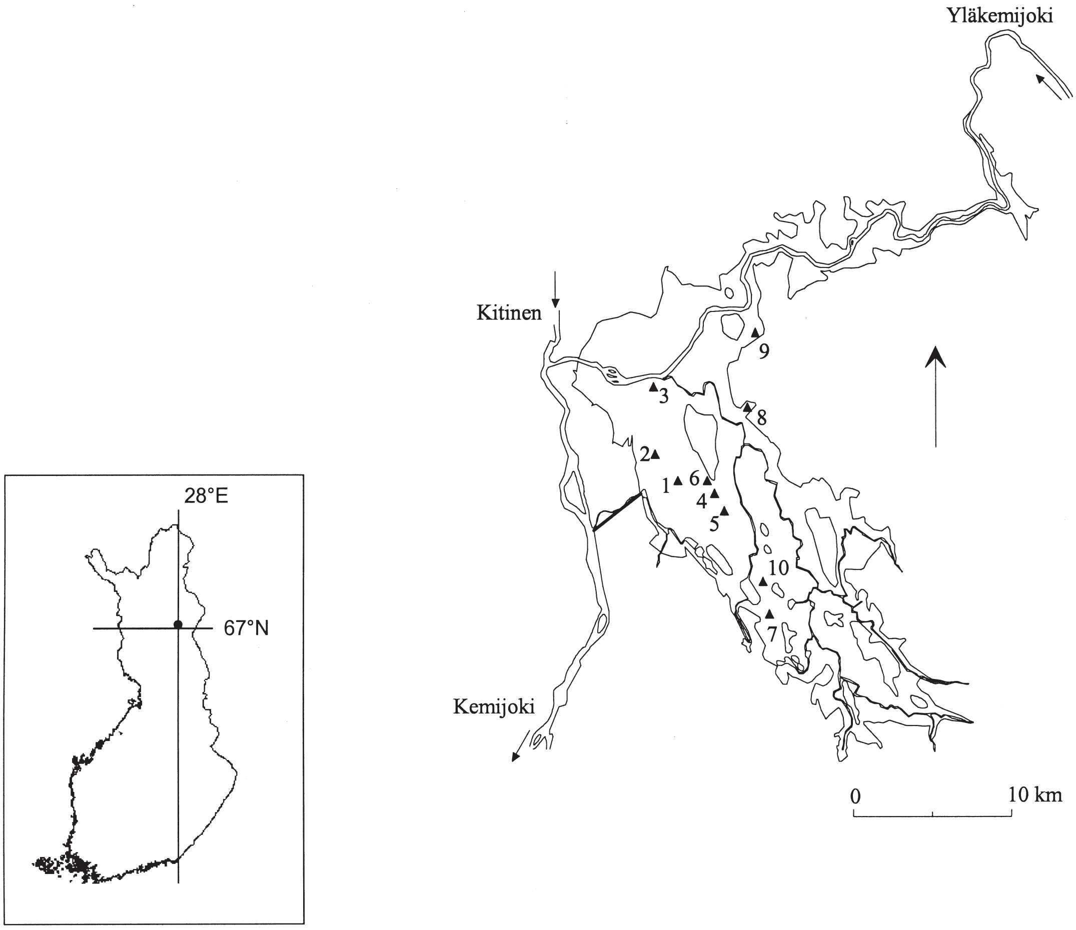

Fig. 1. Location of the study sites in Vuotos, and the area planned for a new hydroelectric reservoir in the northern boreal zone of Finland.

Kuva 1. Tutkimuspaikkojen sijainti Vuotoksella ja uuden vesivoiman tuottoon suunnitellun tekojärven alue Suomen pohjois-boreaalisella vyöhykkeellä.

been considered as a minor source of atmospheric N_2O, but results of their N_2O fluxes are few and variable (Martikainen et al. 1993, 1995, Schiller & Hastie 1994, Nykänen et al. 1995, Regina et al. 1996). In Finland, the N_2O emissions from peatlands have previously been investigated in the southern and middle boreal zones (e.g., Regina et al. 1996), whereas the N_2O fluxes in peatlands of the northern boreal zone rich in minerotrophic fens (Ruuhijärvi 1983) are not known. We measured the fluxes of N_2O at ten natural peatlands in Vuotos, an area planned for a new hydroelectric reservoir in northern Finland. These peatlands have generally shown high CH_4 emissions (Huttunen et al. 2003), with the seasonal averages similar to those reported from minerotrophic fens in the southern and central Finland (Nykänen et al. 1998). The aim of the study was (1) to evaluate the importance of natural peatlands in the northern boreal zone as sources of atmospheric N_2O, and (2) to determine the N_2O fluxes on peatlands in the area of the planned Vuotos Reservoir. The data on the greenhouse gas fluxes in the ecosystems prior to flooding are essential to the assessment of the net greenhouse gas emissions resulting from the possible building of the reservoir.

Material and methods

Study sites

Measurements were conducted on ten natural peatlands situated in the main aapa-mire region (Ruuhijärvi 1982) in Vuotos, located within the municipalities of Pelkosenniemi, Savukoski and Salla in the northern boreal zone in Finland (Fig. 1). Characteristics of the study sites are given in Table 1. The nomenclature of the sites follows Eurola et al. (1995). Vuotos is an area planned for a new hydroelectric reservoir by the Kemijoki Ltd. (Rovaniemi, Finland), a Finnish power company (http://www.kemijoki.fi). Currently, the case of the building of the Vuotos Reservoir is in court (Supreme Administrative Court, Helsinki, Finland). The minimum and maximum surface area of the reservoir would be 55 and 237 km^2, respectively, and the water level regulation 8 m. Peatlands presently cover 60% of the maximum surface area (52% of open fens, 36% of pine fens and 12% of spruce mires), 34% is covered by upland forests and 6% by watercourses. Approximately 10% of the total peatland area in Vuotos has been drained prior to our studies (situation in 1992, Kaisa Kerätär, Kemijoki Ltd., pers. comm.). Karesniemi (1975) has presented a detailed study of peat and peatlands in Vuotos.

The long-term average (1961–1990) annual temperature in Vuotos is around –1.0°C (Finnish Meteorological Institute 1991, measurements at the Sodankylä Observatory, 67° 27´ N, 26° 39´ E, about 60 km northwest from Vuotos). The length of the growing season is around 127 days and the length of snow-cover 208 days. The long-term annual precipitation is 499 mm.

Measurements

Fluxes of N_2O were determined at the study sites by static chamber technique (Nykänen et al. 1995, 1998). Before the measurements were started, wooden boardwalks were constructed at the sites to prevent peat disturbance during sampling. Simultaneously, aluminum collars (dimensions 60 × 60 × 30 cm, 3–6 replicates) were inserted into the peat at each site. During the once–twice a month repeated flux measurements from June to October at all the sites in 1994 and from June to September at site 8 in 1995, aluminum chambers (dimensions 60 × 60 × 15 cm), equipped with battery-operated fans, were attached to water-filled grooves of the collars for 20–30-min meas-

Table 1. Characteristics of the study sites.
Taulukko 1. Tutkimuspaikkojen ominaisuuksia.

Site, abbreviation[a]	Trophic group[b]	Peat thickness (cm)	WT[c] (cm)	Air temp.[c] (°C)	Peat temp.[c] (°C)
1 Mesotrophic flark fen, MeRiN	II	100	–0.3	9.6	10.0
2 Swamp fen, LuN	II	40	0.6	11.0	9.6
3 Oligotrophic tall-sedge pine fen, OlSR	I	90	–14.0	12.0	9.6
4 Oligotrophic flark fen, OlRiN	I	150	–0.4	9.6	8.9
5 Mesotrophic mud-bottom flark fen, MeRuRiN	II	280	–0.3	10.0	10.0
6 Oligotrophic *Sphagnum* flark fen, OlSphRiN	I	295	–0.4	12.0	9.2
7 Eutrophic birch fen, KoL	III	260	2.2	8.9	7.7
8 Herb-grass spruce mire[d], RhK	IV	10	–38.0	8.2	6.6
9 Eutrophic pine fen, LR	III	40	–25.0	8.3	7.8
10 Oligotrophic tall-sedge fen, OlSN	I	120	3.4	8.9	7.9

[a]Nomenclature: Eurola et al. (1995).
[b]Trophic groups: I Minerogenous oligotrophic and oligo-mesotrophic fens, II Minerogenous mesotrophic fens, III Eutrophic fens, and IV Spruce mires.
[c]Mean water table levels (negative below peat surface), and air and peat (at the depth of 20 cm) temperatures for the snow-free period from June to October in 1994.
[d]Mean water table level, air temperature and peat temperature were –13 cm, 13 °C and 8 °C from June to September in 1995, respectively.

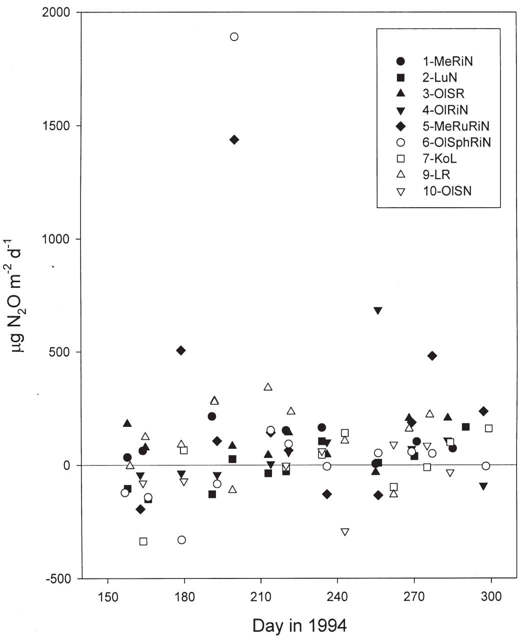

Fig. 2. Seasonal dynamics of N_2O fluxes at nine studied peatlands. The mean values are daily averages.

Kuva 2. N_2O-virtojen kausivaihtelu yhdeksällä tutkitulla suolla. Keskiarvot ovat päiväkeskiarvoja.

uring periods. During the measuring periods, four headspace gas samples were withdrawn from each chamber at 5–10 min intervals into polypropylene syringes (BD Plastipak) equipped with three-way stopcocks (Connecta). The sample N_2O concentrations were analyzed in the laboratory with a HP 5890 Series II gas chromatograph equipped with an electron capture detector (ECD) (for the detailed description of the analysis see Nykänen et al. 1995). The N_2O fluxes were calculated from linear changes in the chamber N_2O concentrations during measuring periods. We also estimated peatland type-weighted N_2O emission for the total peatland area in Vuotos, using three peatland categories with the known percent coverages: open fens (sites 1, 2, 4, 5, 6, 7 and 10), pine fens (sites 3 and 9) and spruce mires (site 8).

During the N_2O flux measurements, water table position was measured with a piezometer (Mannerkoski 1986) from perforated pipes inserted into the peat close to most of the collars. Air temperatures inside and outside the chambers were measured with a Fluke 52 K/J thermometer. Peat temperatures at the peat surface and at the depths of 3, 5, 10, 15, 20, 25, 30, 40 and 50 cm below the surface were also measured.

Table 2. N_2O fluxes from the studied natural northern boreal peatlands in Finland.

Taulukko 2. N_2O-virrat tutkituilta Suomen pohjois-boreaalisilta soilta.

Site	N_2O flux (µg m^{-2} d^{-1})					
	Mean[a]	S.E.[a]	Median[b]	Minimum[b]	Maximum[b]	N[c]
June–October 1994						
1	110	15	100	–640	470	44
2	5.7	50	–46	–290	480	30
3	140	77	79	–210	570	30
4	72	65	39	–410	1400	30
5	230	67	170	–520	2700	32
6	103	78	–38	–680	3300	70
7	–2.9	34	11	–580	680	45
8	940	121	470	–67	5000	24
9	130	30	110	–640	1000	30
10	–30	20	–11	–620	300	24
June–September 1995						
8	290	45	260	30	680	24

[a]The means and their standard errors are calculated by averaging monthly averages from 3–6 replicate collars at each site.
[b]Median, minimum and maximum values were obtained from individual chamber measurements.
[c]N is the number of individual chamber measurements.

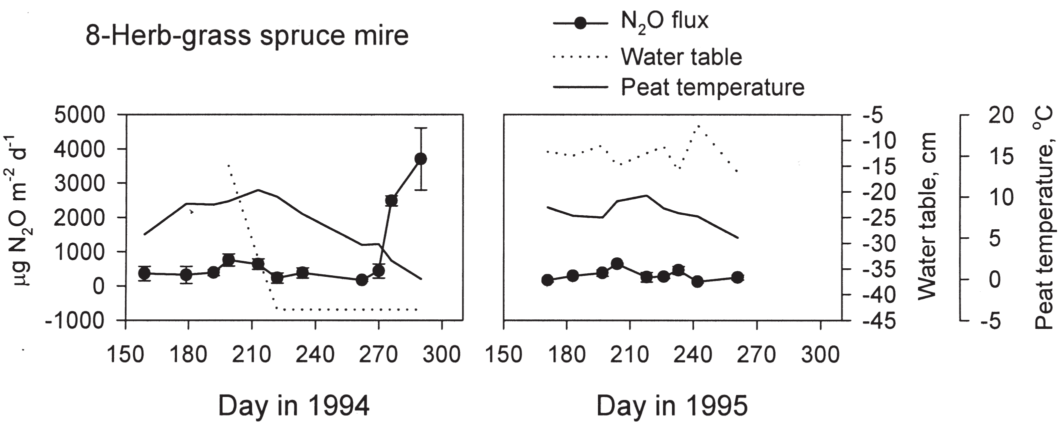

Fig. 3. Seasonal dynamics of N_2O flux, water table level and peat temperature (at the depth of 20 cm) at the herb-grass spruce mire (site 8-RhK). The mean values are daily averages and the error bars in the N_2O fluxes are standard errors of the mean.

Kuva 3. N_2O-virran, vedenpinnan korkeuden ja turpeen lämpötilan (20 cm:n syvyydellä) kausivaihtelu ruoho- ja heinäkorvessa (paikka 8, RhK). Keskiarvot ovat päiväkeskiarvoja ja virherajat N_2O-virroissa keskiarvon keskivirheitä.

Statistical analyses

Pearson correlation coefficients (for normally distributed variables) and Spearman's rank correlation coefficients (for non-normally distributed variables) were used to study the relations between N_2O fluxes, peat moisture and temperature conditions. Kruskal-Wallis analysis of variance was used to test the statistical significance of the differences in the N_2O fluxes between the sites, and the multiple comparisons of means was performed as presented by Siegel & Castellan (1988, pp. 213–214). The significance of the between-year difference in the N_2O fluxes was tested with the Mann-Whitney U-test. SPSS statistical package (release 9.0.1) was used for the statistics.

Results

Seasonal variations in the N_2O fluxes and relations between fluxes and peat moisture and temperature conditions

Daily N_2O fluxes showed large seasonal variation (Fig. 2, Fig. 3, Table 2). The N_2O flux varied in individual chamber measurements from uptake of atmospheric N_2O to high emission, from –680 to 5000 µg m^{-2} d^{-1} (Table 2). Generally, the N_2O fluxes were not related to seasonal changes in the water table level or peat temperature; the N_2O flux correlated with temperature only at the site 2 at a depth of 30 cm (Pearson correlation coefficient $r = –0.36$, $n = 30$, $p < 0.05$). At the herb-grass spruce mire (site 8), substantial increase in the N_2O release was observed in October 1994, when peat temperatures felt close to 0 °C (Fig. 3). A similar increase was not observed in 1995, when the last measurement was made in September with peat temperatures still around 5 °C (Fig. 3). At the site 8, the water table level was higher in 1995 than in 1994, due to higher precipitation (Finnish Meteorological Institute 1995, 1996) (Fig. 4). Air temperatures were nearly similar between the study years (Finnish Meteorological Institute 1995, 1996) (Fig. 4).

Mean N_2O fluxes

The seasonal mean N_2O fluxes also varied from uptake to emission, ranging from –30 to 940 µg m^{-2} d^{-1} (Table 2). Sites 2, 7 and 10 had low mean N_2O fluxes, ranging from –30 to 5.7 µg m^{-2} d^{-1} (Table 2) with the mean water tables above the peat surface (Table 1). In 1994, the driest site, the herb-grass spruce mire (site 8), showed the highest mean N_2O emission, 940 µg m^{-2} d^{-1}. Other

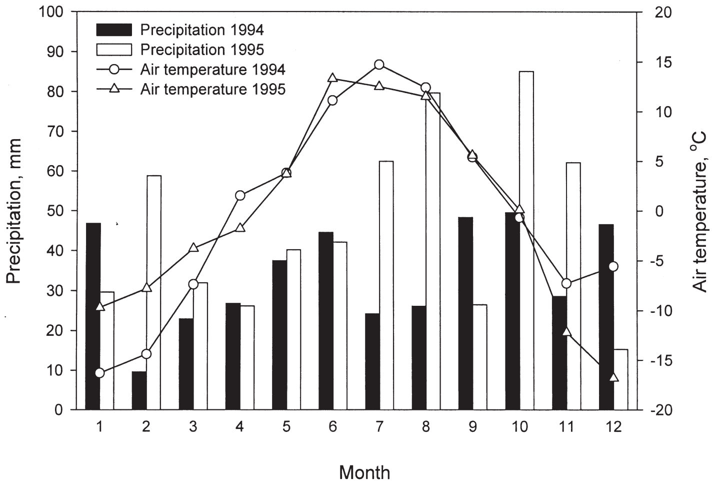

Fig. 4. Precipitation and air temperature in the study years 1994 and 1995, measured at the Sodankylä Observatory near Vuotos (Finnish Meteorological Institute 1995, 1996).

Kuva 4. Sademäärä ja ilman lämpötila tutkimuksen aikana 1994 ja 1995, mitattuna Sodankylän Observatoriossa lähellä Vuotosta (Finnish Meteorological Institute 1995, 1996).

sites where the water table was below the peat surface (Table 1) had the average fluxes of 72–230 µg N_2O m^{-2} d^{-1} (Table 2). The peatland type-weighted average N_2O emission from the peatlands in Vuotos was 178 µg N_2O m^{-2} d^{-1}, i.e. 23 mg N_2O m^{-2} yr^{-1}.

The Kruskal-Wallis analysis of variance indicated statistically significant differences in the mean N_2O fluxes at the collars between the study sites ($\lambda^2 = 21.0$, $n = 38$, $p < 0.05$). The multiple comparisons of means showed that only the fluxes at the driest site 8 were significantly ($p < 0.05$) higher than those at the wettest sites 7 and 10. The difference in the mean N_2O fluxes between the study years (June–September in 1994 and 1995) at site 8 was not statistically significant (Mann-Whitney U-test, $U = 1.00$, $p > 0.05$). The seasonal mean N_2O fluxes at the study sites correlated with the mean water table levels (Spearman's rank correlation coefficient $\rho = -0.81$, $n = 10$, $p < 0.05$) (Fig. 5). The correlation was still found after removal of the driest site 8 with the highest N_2O emission from the data (Spearman's rank correlation coefficient $\rho = -0.73$, $n = 9$, $p < 0.05$).

Discussion

The seasonal mean N_2O fluxes of the studied natural northern boreal peatlands were generally low. In 1994, the fluxes varied from –30 to 230 µg N_2O m^{-2} d^{-1} (–3.8 to 29 mg m^{-2} annually, 127 d active period assumed) at the sites with the mean water tables between –25 and 3.4 cm. These correspond to the average N_2O fluxes of –30 to 200 µg m^{-2} d^{-1} measured from natural southern and middle boreal peatlands in Finland with the water tables from –28 to –4 cm (Regina et al. 1996). In the Hudson Bay lowland peatlands, Canada, annual N_2O fluxes have ranged from –5.7 to 18.5 mg m^{-2} (Schiller & Hastie 1994), which also are consistent with the fluxes measured in Vuotos (this study) and other natural peatlands in Finland (e.g., Regina et al. 1996). Thus, natural boreal peatlands with high water tables are barely important sources of atmospheric N_2O as stated by Martikainen et al. (1993). At the herb-grass spruce mire (site 8), the mean N_2O release was 940 µg m^{-2} d^{-1} in 1994 (120 mg m^{-2} annually, 127 d active period assumed), similar or higher than the N_2O fluxes on drained boreal peatlands (means from –5.3 to 900 µg N_2O m^{-2} d^{-1}, Regina et al. 1996) or mineral agricultural soils (means 260–2500 µg m^{-2} d^{-1}, Regina et al. 2001) in Finland during the summer. In farmed organic soils and afforested organic agricultural soils much higher mean summertime N_2O emissions, 2500–4700 µg m^{-2} d^{-1}, have been reported (Maljanen et al. 2001, Regina et al. 2001). It must be stressed that N_2O exchange was not measured at our study sites during winter, which could underestimate the annual N_2O emissions. However, according to Alm et al. (1999) natural boreal peatlands have negligible N_2O fluxes during winter, whereas on drained boreal peatlands wintertime N_2O release

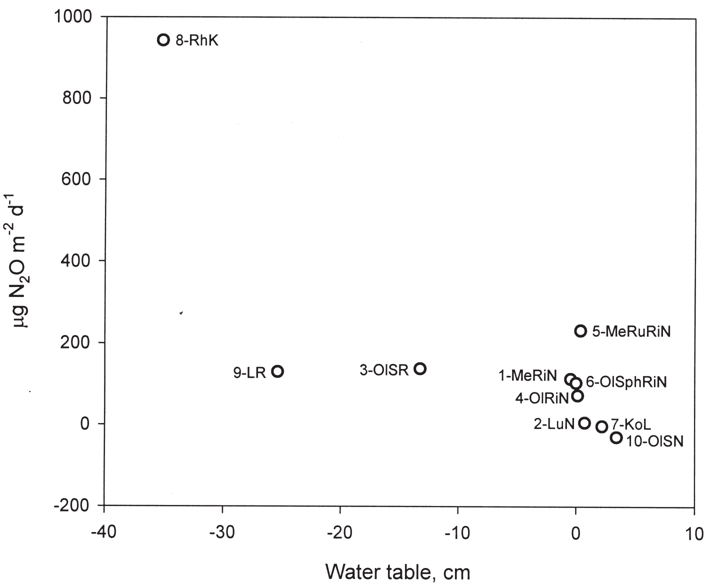

Fig. 5. The mean N_2O fluxes plotted against the mean water table levels at the studied northern boreal peatland sites. The means are calculated by averaging monthly averages in 1994 from 3–6 replicate collars at each site.

Kuva 5. Tutkittujen pohjois-boreaalisten soiden N_2O-virtojen keskiarvot vedenpinnan korkeuden keskiarvojen funktiona. Keskiarvot on laskettu kuukausikeskiarvoista (vuoden 1994 tulokset, 3–6 kaulusta kullakin suolla).

can contribute up to 28% to the annual emissions. This agrees with our results from October 1994, when only the driest site 8, the herb-grass spruce mire, showed substantially increased N_2O release at low peat temperatures. Large but highly episodic N_2O emissions have been found from various soils during freezing and thawing periods (for a review see Martikainen 2002). The N_2O emissions during cold season have contributed 28–70% to the annual N_2O release from various soils, but processes which increase the N_2O emissions at low temperatures are still poorly understood (Martikainen 2002).

The statistical relation between mean N_2O fluxes and water table levels has been presented for peatlands including both natural and drained counterparts in the southern and middle boreal zones in Finland (Regina et al. 1996). The significant correlation between the mean N_2O fluxes and water tables was also observed in the natural northern boreal sites in this study. This confirms the close association between N_2O release and oxygen conditions in peat. The higher oxygen availability in the uppermost peat profile generally allows higher nitrogen mineralization and higher nitrification, and thus, may enhance the N_2O production via coupled nitrification and denitrification (Davidson & Schimel 1995). In highly anoxic conditions, denitrification can consume N_2O, which probably was the reason for the observed negative N_2O fluxes, i.e. the uptake of atmospheric N_2O at the wettest study sites. Nitrous oxide uptake has also been found in other natural boreal peatlands (Schiller & Hastie 1994, Regina et al. 1996). The close association between the N_2O fluxes and water table levels on natural peatlands found in this study agree with the observed increases in the N_2O emissions from northern peatlands after artificial drainage (Martikainen et al. 1993, 1995, Regina et al. 1996). Drainage has increased N_2O emissions mainly from minerotrophic peatlands (fens), whereas changes in the N_2O fluxes in ombrotrophic peatlands (bogs) have been small (Martikainen et al. 1993, 1995, Regina et al. 1996). The experimental lowering of the water table has also increased N_2O release from peat in the laboratory (Freeman et al. 1993, Regina et al. 1998). In northern regions, an increase in soil N_2O release has been expected, due to thawing of permafrost associated with climate warming (Khalil & Rasmussen 1989). Winter precipitation is predicted to increase whereas summer precipitation would not drastically change in northern Europe (IPCC 2001b), thus any major increase in the N_2O emissions from natural northern boreal peatlands in Finland could not be expected in the future.

The peatland type-weighted preflood N_2O emission from the entire peatland area in Vuotos was low, because the open fens and pine fens with the low N_2O release covered the majority of the total peatland area. Natural ponds and 25–28 years ago constructed hydroelectric reservoirs (Lokka and Porttipahta) in the northern boreal zone in Finland have shown low N_2O fluxes during the open water season, with averages ranging from –89 to 270 µg m^{-2} d^{-1} (Huttunen et al. 2002a,b). Thus, it is unlikely that the possible Vuotos reservoir, including the flooded peatlands, would have high N_2O emissions after flooding. However, the short-term N_2O emissions from newly created reservoirs are unknown. The emissions of methane (CH_4) and carbon dioxide (CO_2) are found to be large over some years after flooding (Kelly et al. 1997, Scott et al. 1999) and even after decades of impounding these emissions could exceed those in natural oligotrophic-mesotrophic lakes (Huttunen et al. 2002b). Seasonally flooded bottoms in freshwater reservoirs are estimated to be important sources of N_2O to the atmosphere (Fearnside 1997), corresponding to occasionally irrigated or drying and wetting soils with enhanced N_2O release (Davidsson & Leonardson 1997, Wulf et al. 1999). Due to the great water level regulation of 8 m, the minimum surface area of the planned Vuotos reservoir would be 55 km^2, which is small compared to the maximum area of 237 km^2. It is difficult to predict the risk for increased N_2O emissions from the temporarily flooded area, because the annual water level regulation in the reservoir would take place during winter ice-cover and the maximum water level would be maintained during the open water season.

Acknowledgements

Eija Konttinen (†) and Mirja Borgman are appreciated for laboratory assistance, and Aapo Nenonen, Juha Kokko and Arto Niskanen for their help in the field. University of Kuopio, Kemijoki Ltd., Finnish Cultural Foundation and Niilo Helander Foundation financially supported this work. Carrie Turunen kindly revised the language. Dr. Kristiina Regina and Dr. Kari Minkkinen are acknowledged for their comments on the manuscript.

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TIIVISTELMÄ:

Typpioksiduulivirrat suunnitellun Vuotoksen tekojärven alueen soilta

Dityppioksidi (N_2O) on haitallinen kaasu ilmakehässä, sillä kasvihuonekaasuna se aiheuttaa ilmaston liiallista lämpenemistä, ja osallistuu lisäksi myös stratosfäärin otsonikerroksen tuhoamiseen. Tässä työssä tutkittiin N_2O-virtoja kymmenellä luonnontilaisella suolla suunnitellun Vuotoksen tekojärven alueella Suomen pohjoisboreaalisella vyöhykkeellä. Tutkituilla soilla N_2O-virrat olivat yleensä pieniä ja keskimääräiset N_2O-virrat korreloivat negatiivisesti tutkimuspaikkojen keskimääräisen vedenpinnan tason kanssa, eli N_2O-päästö pieneni suon märkyyden lisääntyessä. Kuivimmalla tutkimuspaikalla, ruoho- ja heinäkorvessa, N_2O-päästöt olivat suurimmat, keskimääräisesti 940 ja 290 µg m^{-2} d^{-1} lumettomana aikana 1994 ja 1995. Suotyypeillä painotettu keskimääräinen N_2O-päästö Vuotoksen alueen soilta oli 178 µg m^{-2} d^{-1}. Tämän perusteella pohjoisboreaaliset suot eivät ole luonnontilaisina tärkeitä dityppioksidin päästölähteitä ilmakehään. Pitkäaikaiset N_2O-päästöt mahdollisen Vuotoksen tekojärven ulappa-alueelta jäävät todennäköisesti myös vähäisiksi, mutta ajoittain upoksissa olevan säännöstelyvyöhykkeen merkitys kokonaispäästöihin on tuntematon. Veden pinnan noston jälkeisiä lyhytaikaisia N_2O-virtoja ei ole boreaalisissa tekojärvissä tutkittu.

Received 8.10.2002, Accepted 9.12.2002