REGULAR ARTICLE

# Nitrous oxide and methane fluxes of a pristine slope mire in the German National Park Harz Mountains

Nadine Tauchnitz · Rainer Brumme ·
Sabine Bernsdorf · Ralph Meissner

**Abstract** Pristine peatlands covered by Histosols (bogs and fens) with high water table and a restricted oxygen ($O_2$) availability are known to have low emissions of nitrous oxide ($N_2O$) but may be a significant source for atmospheric methane ($CH_4$) which are both important greenhouse gases. For the first time $N_2O$ and $CH_4$ fluxes of a pristine slope mire in the German Harz Mountains have been monitored. Previously reported peatlands are characterised by anaerobic conditions due to high water table levels. Slope mires monitored here receive $O_2$ through slope water inflow. Gas fluxes have been monitored deploying closed chamber method on a central non-forested area and a forested area at the periphery of the slope mire. By means of groundwater piezometers water table levels, ammonium and nitrate contents as well as hydro-chemical variables like oxygen content and redox potential of the mire pore water have been concurrently measured with trace gas fluxes at both monitoring sites of the slope mire. The slope mire took up small amounts of atmospheric methane at a rate of $-0.02\pm0.01$ kg C ha$^{-1}$ year$^{-1}$ revealing no significant difference between the forested and non-forested site. Higher uptake rates were observed during low water table level. In contrast to pristine peatlands influx of oxygen containing pore water into slope mire does limit reduction processes and resultant $CH_4$ emission. $N_2O$ fluxes of the forested and non-forested sites of the slope mire did not differ and amounted to $0.25\pm0.44$ kg N ha$^{-1}$ year$^{-1}$. Higher emissions were observed at low water table levels and during thawing periods. In spite of favourable conditions $N_2O$ fluxes of the slope mire have been comparable to those of pristine peatlands.

**Keywords** Groundwater movement · Methane · Nitrous oxide · Oxygen availability · Peatlands · Slope mires

N. Tauchnitz (✉) · S. Bernsdorf
Institute of Agricultural and Nutritional Sciences,
Faculty of Natural Sciences III,
Martin-Luther-University Halle-Wittenberg,
06099 Halle, Germany
e-mail: nadine.boehlmann@landw.uni-halle.de

R. Brumme
Institute of Soil Science and Forest Nutrition,
University of Goettingen,
Buesgenweg 2,
37077 Goettingen, Germany

R. Meissner
Department of Soil Physics,
Helmholtz Centre for Environmental Research – UFZ,
Lysimeter Station, Dorfstraße 55,
39615 Falkenberg, Germany

## Introduction

Natural peatlands, covered by Histosols (FAO/ISRIC/ISSS 1998), are important sinks for carbon (C) and nitrogen (N) due to prevailing permanent anaerobic

conditions and resultant low rates of decomposition (Moore et al. 2004). They represent only about 3% ($3.88–4.38 * 10^6$ km$^2$) of the world's area but comprise up to 30% of their C and N reserves (Martikainen et al. 1993). Thus, peatlands play an important role in the global C and N cycle and they may also contribute significantly to the production and consumption of the greenhouse gases nitrous oxide ($N_2O$; Martikainen et al. 1993; Regina et al. 1996; Regina et al. 2004) and methane ($CH_4$; Augustin et al. 1996; Khalil 1999) but have not been considered in respective global estimates (Brumme et al. 2005) due to large uncertainties resulting from the diversity of peatlands.

The global warming potentials (GWP) of nitrous oxide ($N_2O$) and methane ($CH_4$) are 310 and 21 times, respectively, than that of $CO_2$ during a 100 year time scale (IPCC 2007). $N_2O$ is mainly produced in soils due to autotrophic nitrification and heterotrophic denitrification (Davidson 1991). Virgin peatlands with natural high water table levels show low $N_2O$ fluxes or consumption of $N_2O$ due to limitation of oxygen and hence absence of nitrification resulting in low $NO_3^-$ concentrations (Martikainen et al. 1993; Augustin et al. 1996; Regina et al. 1996; Aerts 1997; Brumme et al. 1999).

The greenhouse gas $CH_4$ is produced during the anaerobic decomposition processes in anoxic parts of peats by methanogenic bacteria whereas it is oxidized in the presence of free oxygen by methanotrophic bacteria (Joabsson et al. 1999). Pristine peatlands are a significant source of $CH_4$ to the atmosphere. Three emission pathways have been reported for $CH_4$: molecular diffusion of dissolved $CH_4$, ebullition (bubbling) of $CH_4$ and transport of $CH_4$ through plant roots and shoots (Tokida et al. 2005).

Previous studies have pointed out that both groundwater table levels and temperature mostly affected the fluxes of trace gases in peatlands (Augustin et al. 1996; Koponen and Martikainen 2004). The few studies of greenhouse gas emissions from virgin peatlands have been conducted in classical bogs and fens without permanent water inflow (e. g. Martikainen et al. 1993; Regina et al. 1996; Heikkinen et al. 2002). Reports of $N_2O$ and $CH_4$ fluxes from slope mires, a peatland type widespread in mountain forests are lacking. Globally slope mires represent 1% of the world's peatlands comprising an area of about 4 million hectare (Joosten, 2007, personal communication). Solely the different movement of soil water in slope

mires should change controlling factors of gas formation and resulting greenhouse gas fluxes. We hypothesize that slope mires release more $N_2O$ because of increased influx of $O_2$ which inhibits $N_2O$ reductase and concurrently restricts $N_2$ formation. The influx of $O_2$ might adversely affect $CH_4$ formation and might favour $CH_4$ oxidation resulting in lower $CH_4$ emission from slope mires than that of pristine bogs and fens.

To test these hypotheses we conducted a field experiment in a pristine slope mire at the Harz Mountains with the following objectives:

1. To quantify and to compare fluxes of $N_2O$ and $CH_4$ in mire zones at a central non-forested and a peripheral forested area representing different nutrient status, water table levels and oxygen input caused by slope water inflow
2. To monitor N contents and other relevant features of mire pore water in order to identify relationships to the production and consumption of $N_2O$ and $CH_4$
3. To find out seasonal dynamics of $N_2O$ and $CH_4$ fluxes

## Materials and methods

### Study site

The study was conducted in the Harz mountains, central Germany (federal state Saxony-Anhalt), close to the highest peak of the Harz mountain (Mt Brocken, 1,142 m a.s.l., 51°48′N, 10°37′E) at an elevation of 843–860 m a.s.l. Springs of the Ilse stream characterize features of the studied area (Böhlmann et al. 2005). Average annual precipitation (1951–1980) amounts to 1,609 mm and mean annual temperature is +2.8°C (Wegener and Kison 2002). The annual bulk N deposition at the mire was about 51 kg ha$^{-1}$ year$^{-1}$ in 2003 of which 25 kg ha$^{-1}$ year$^{-1}$ was deposited as nitrate (Böhlmann 2004).

The investigated mire comprising Fibric Histosols covers a slope of 0.015 km$^2$ which is part of a catchment of 0.13 km$^2$. The mire was formed about 1,000 years ago ($^{14}$C analysis, Böhlmann 2004) on granite debris of the Mt Brocken. The thickness of the peat layer is up to 1.4 m. The largest part of the slope mire is a swamp overgrown with spruce plants (0.01 km$^2$) and a Calamagrostio villosae-Piceetum-

community. Vegetation of the central part of the mire is dominated by a *Eriophorum angustifolium*-community and is mostly free of spruce trees (Böhlmann et al. 2005).

### Field sampling and analysis

Fluxes of $N_2O$ and $CH_4$ were measured biweekly with the closed chamber method during the study period that lasted from 19 June 2002 to 9 July 2003. Measurements have not been made at days with high snow cover during winter from November to March. For flux measurements, 10 chambers consisting of PVC rings (30 cm height, 30 cm diameter) were installed into the peat and remained throughout the entire study period. Four chambers were set up at the peripheral forested site and six chambers at the central non-forested site of the slope mire. Gas samples were taken at 0, 20 and 40 min after closing the chambers with a lid using evacuated glass flasks (100 ml). Before sampling, air pressure of the glass flasks was checked by pressure sensor (Loftfield et al. 1997). Air temperature was measured at a height of 2 m and soil temperatures were measured in 2.5, 5, 10 cm soil depth during gas sampling periods. The gas samples were analysed within few days by an automated gas chromatographic system consisting of a computer-controlled gas chromatograph (Carlo Erba) equipped with a flame ionization detector (FID) for $CH_4$, an electron capture detector (ECD) for $N_2O$ measurements, and an autosampler for 64 sample flasks (Loftfield et al. 1997).

Peat samples were taken at the beginning of measurements in June 2002 next to the chambers from a depth of 0–20 cm. Air-dried peat samples were analysed for total C ($C_t$) and N ($N_t$) with an elemental analyzer (Hanau, Germany). The pH of the peat samples was determined after shaking with 0.01 M $CaCl_2$. $NH_4^+$ and $NO_3^-$ of the peat samples have been extracted with a 2 M KCl-solution and analysed with a continuous-flow-analyser (Skalar, Netherlands) using the indophenol-blue method.

Groundwater piezometers were placed in the peat layer adjacent to the chambers. The groundwater piezometers were used to measure water table levels (WT), redox potentials (Eh, WTW, Germany), and oxygen levels ($O_2$, WTW, Germany) at the time of gas measurements. Measurements were performed at a depth of 30 dcm. Furthermore, water samples were collected and analysed for ammonium, nitrate, pH (WTW, Germany) and electric conductivity (EC) (WTW, Germany).

### Statistical analyses

All statistical analyses were performed using a SAS software package [SAS Institute (1999–2001), Inc., Cary, USA, Release 8.2] and Statistica for Windows v. 5.1 (StatSoft, Inc. 1996, Tulsa). Pearson correlation coefficients were calculated to elucidate relationships between gas fluxes, soil temperature and variables of mire pore water. One-way analysis of variance (ANOVA) has been used to test significance of differences between gas fluxes at the forested and non-forested part of the mire. Data were tested for normality and equality of variance before statistical analyses.

## Results

### Soil temperature, water table, peat soil, mire pore water

Thickness of peat differed significantly ($p<0.05$, $n=4$, Table 1) between the central and peripheral site of the mire being 105 and 56 cm respectively. Top layer (0–20 cm) of peat at both locations showed similar pH, bulk density, total N and C:N ratio while nitrate content was higher in the forested area of the mire ($p<0.05$, $n=4$, Table 1).

**Table 1** Characteristics of the peat soil (*Fibric Histosol*) at the forested peripheral and the non-forested central area of the slope mire (0–20 cm depth, $n=4$)

|  | Forested area | Non-forested area |
|---|---|---|
| Peat layer thickness (cm) | 56.2±5 | 105±6* |
| Bulk density (g cm$^{-3}$) | 0.14±0.08 | 0.06±0.01 |
| pH | 3.9±0.2 | 3.9±0.03 |
| EC (μS cm$^{-1}$) | 191±17 | 122±39 |
| $NH_4$ (mg N kg$^{-1}$) | 65.6±3 | 96.3±51 |
| $NO_3$ (mg N kg$^{-1}$) | 24.1±15 | 4.2±1* |
| $N_t$ (%) | 1.6±0.2 | 1.4±0.2 |
| C:N | 24±0.2 | 29±4.8 |

Data are means ± SD (standard deviation)
*$p<0.05$ (Tukey Test)

Not being different between soil depth soil temperatures ranged from −0.1 to 19.6°C for the dates monitored (Fig. 1a). Water table levels differed significantly between the forested and non-forested areas ($p < 0.05$, $n = 16$, Fig. 2a). At the peripheral forested area, water table levels varied between −1 and −10 cm below the mire surface and between −4 and −27 cm at the central non-forested part of the mire. The highest water table levels were found during snow melting in April 2003, the lowest in July 2002.
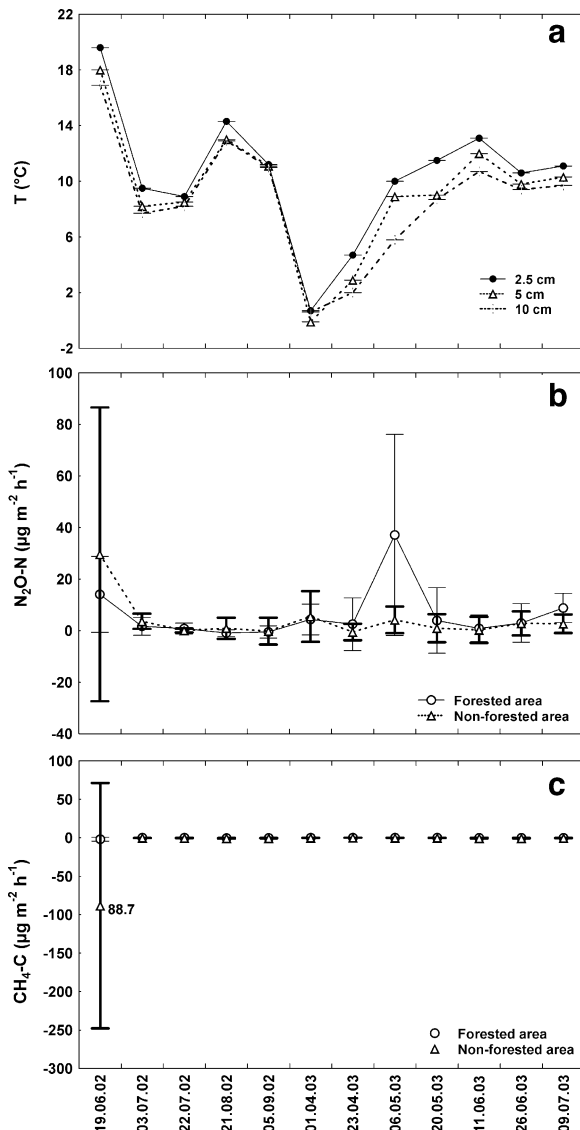


Fig. 1 **a–c**: Seasonal pattern of soil temperatures (°C) (**a**) and gas fluxes of $N_2O$ (**b**) and $CH_4$ (**c**) ($\mu g\ m^{-2}\ h^{-1}$) at the forested and non-forested monitoring sites of the slope mire (means with standard deviations)



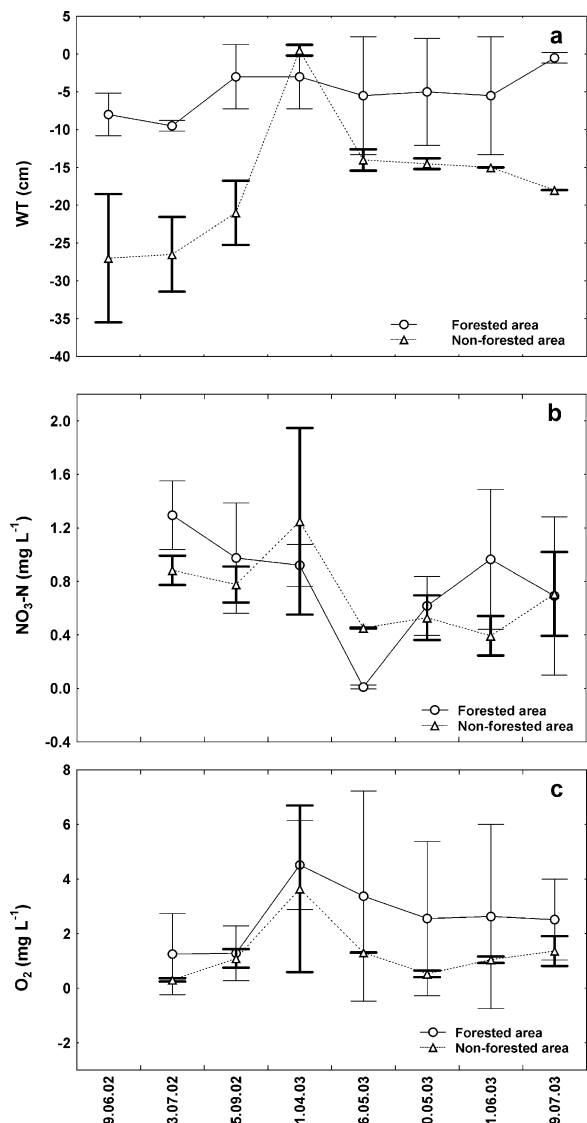Fig. 2 **a–c**: Seasonal patterns of water table levels (WT, cm) (**a**), nitrate concentrations (mg $L^{-1}$) (**b**) and oxygen concentrations (mg $L^{-1}$) of the mire pore water at the forested and non-forested monitoring sites of the slope mire (means with standard deviations)

Pattern of pore water characteristics followed the temporal variation of the water level. Values of $O_2$ being low during low water table levels in summer increased with water table in winter and peaked in April. On average the redox potential was 150 mV and 14 mV and $O_2$ content averaged 2.6 mg $L^{-1}$ and 1.4 mg $L^{-1}$ at the forested and non-forested area, respectively. Resulting from a considerable spatial variation of $O_2$ and Eh in pore water (Table 2) these values did not significantly differ. Values of pH,

**Table 2** Hydro-chemical variables of mire pore water at the forested peripheral and the non-forested central area of the slope mire during the study period (30 cm depth, $n=16$)

|  | Forested area | Non-forested area |
| --- | --- | --- |
| Water table (cm) | −4.6±2.8 | −16.7±5.9* |
| Temperature (°C) | 7.1±3.2 | 10.2±3.9 |
| Eh (mV) | 149±130 | 14±95 |
| $O_2$ (mg $L^{-1}$) | 2.6±2.2 | 1.4±0.6 |
| EC (µS $cm^{-1}$) | 53±11 | 34±6* |
| pH | 4.4±0.5 | 4.5±0.3 |
| $NH_4$ (mg N $L^{-1}$) | 0.17±0.1 | 0.13±0.1 |
| $NO_3$ (mg N $L^{-1}$) | 0.78±0.4 | 0.71±0.3 |
| $N_t$ (mg $L^{-1}$) | 1.83±0.5 | 1.48±0.4 |
| TOC (mg $L^{-1}$) | 10.78±9.6 | 15.37±1.86 |

Data are means ± SD (standard deviation)

*$p<0.05$ (Tukey Test)

ammonium, total N and EC remained relatively constant during the study (not shown) while nitrate showed some variations with lowest values in May 2003 (Fig. 2b). In contrast to pH and values of ammonium and nitrate concentrations the conductivity of pore water differed significantly ($p<0.05$, $n=16$) between the forested and non-forested areas of the mire averaging 53 and 34 µS $cm^{-1}$ respectively.

### $N_2O$

The $N_2O$ emissions ranged between −0.9 and +37.1 µg $m^{-2}$ $h^{-1}$ with peak emissions at the 19th June 2002 and 6th May 2003 (Fig. 1b).

No relationships were found between $N_2O$ release of the mire and soil temperature, water table level, Eh and ammonium concentration. Negative correlations were observed between $N_2O$ release and $O_2$ contents at the central part of the mire and between $N_2O$ release and nitrate for the one measuring point only at the peripheral part of the mire (Table 3). Mean annual $N_2O$ emissions did not differ significantly between the sites and amounted to 0.4±0.5 kg N $ha^{-1}$ $year^{-1}$ at the forested and 0.2±0.4 at the non-forested site.

### $CH_4$

The mire was found to be a $CH_4$ sink at almost all sampling dates (Fig. 1c). The annual $CH_4$ uptake of the mire adds up to −0.02±0.01 kg $ha^{-1}$ $CH_4$-C. The highest uptake of −88.7 µg $m^{-2}$ $h^{-1}$ occurred during low level of water table at the 19th June 2002. At all other observation dates $CH_4$ fluxes of the mire varied around zero with $CH_4$ rates of −1.8 to 0.005 µg $m^{-2}$ $h^{-1}$. The exceptional singular high peak uptake does cause the significant correlation between $CH_4$ uptake and soil temperature (Table 3). None of the other variables revealed a significant correlation to $CH_4$ fluxes. $CH_4$ fluxes amounted to −0.01±0.01 kg $ha^{-1}$ $year^{-1}$ at the forested and −0.02±0.01 kg $ha^{-1}$ $year^{-1}$ at the non-forested areas and did not differ significantly.

## Discussion

### Temporal pattern of $N_2O$ emission

Two $N_2O$ emission peaks observed in this study could be classified as event-related emissions according to Brumme et al. (1999). One $N_2O$ peak of 30 µg $m^{-2}$ $h^{-1}$ was measured at the central part of the mire on 19th June 2002 during low water table level. The second high $N_2O$ release on 06th May 2003 followed a freezing–thawing periods. Increased $N_2O$ emissions during the freezing–thawing cycles have been

**Table 3** Pearson correlation coefficients between gas fluxes (µg $m^{-2}$ $h^{-1}$), soil temperature (°C), water table levels and hydro-chemical variables of mire pore water at the forested peripheral (P) and the non-forested central area of the slope mire (C)

|  |  | $N_2O$-N | $CH_4$-C |
| --- | --- | --- | --- |
| Soil temperature, 2.5 cm | P | 0.02 | −0.42* |
|  | C | 0.23 | −0.30* |
| Soil temperature, 5 cm | P | 0.01 | −0.41* |
|  | C | 0.22 | −0.29* |
| Soil temperature, 10 cm | P | −0.12 | −0.43* |
|  | C | 0.22 | −0.29* |
| Water table[a] (cm) | P | −0.27 | 0.08 |
|  | C | −0.69 | 0.45 |
| Eh (mV) | P | 0.21 | −0.13 |
|  | C | −0.39 | 0.72 |
| $O_2$ (mg $L^{-1}$) | P | −0.17 | 0.66 |
|  |  | −0.76* | 0.40 |
| $NO_3$ (mg N $L^{-1}$) | P | −0.79* | 0.04 |
|  | C | −0.38 | 0.55 |
| $NH_4$ (mg N $L^{-1}$) | P | −0.18 | 0.53 |
|  | C | −0.33 | 0.01 |
| pH | P | 0.14 | −0.66 |
|  | C | 0.18 | −0.50 |

*$p<0.05$ (Tukey Test)

[a] Water table levels below the mire surface

reported by several other studies (Teepe et al. 2000; Koponen and Martikainen 2004; Koponen et al. 2006). Soil thawing has been suggested to favour denitrification processes due to high water saturation and limited $O_2$ diffusion (Teepe et al. 2000). Furthermore freezing of soils destroys microbial cells providing substrates for denitrifying microbes (Papen and Butterbach-Bahl 1999). Inhibition of $N_2O$ reductase at low temperatures was discussed also as a reason for high $N_2O$ release during freezing–thawing cycles (Melin and Nommik 1983). Several authors reported that increasing nitrate concentrations in liquid water during frost enhance $N_2O$ production (Stähli and Stadler 1997).

With the exception of the event-related emissions $N_2O$ fluxes remained low at both sites despite differences in water table levels. $N_2O$ release of peatlands has been reported to be mainly affected by water table and nutrition status (Martikainen et al. 1993; Augustin et al. 1996; Regina et al. 1996; Brumme et al. 1999). Negative relationships between emitted $N_2O$ amounts and water table levels have been established in various studies (Maljanen et al. 2003; Drösler 2005) due to increases of $O_2$ availability promoting nitrification in drier peat that either increased $N_2O$ formation or produce $NO_3^-$ as precursor of denitrification (Seitzinger 1994; Regina et al. 1996). Very high $N_2O$ emissions between 25 and 72 kg $N_2O$-N ha$^{-1}$ within 46 weeks were observed in single chambers at a drained alder forest in Bornhöved, Germany (Brumme et al. 1999). $N_2O$ emissions up to 27 kg $N_2O$-N ha$^{-1}$ year$^{-1}$ have been monitored at newly drained peatlands with a decreasing water table level down to −60 cm (Augustin et al. 1998). Similar drainage caused high $N_2O$ releases up to 79 μg m$^{-2}$ h$^{-1}$ for a short time (Dorwick et al. 1999). Several authors observed annual $N_2O$ emission rates of >1 kg N ha$^{-1}$ at mean water table levels of −23 to −50 cm (Regina et al. 1996; Augustin et al. 1998; Drösler 2005). Commonly found higher water table levels in our study might be the reason for the generally observed low $N_2O$ emission.

Annual $N_2O$ fluxes

Annual mean $N_2O$ fluxes amounting to 0.25 kg $N_2O$-N ha$^{-1}$ did not statistically differ between the monitoring sites at the mire. These fluxes are in line with those reported for various studies of pristine bogs

and fens with high water table levels (Martikainen et al. 1993; Augustin et al. 1996; Regina et al. 1996; Drösler 2005). Hence our hypothesis that raising $O_2$ input through flowing water increases $N_2O$ release from mire water below the water table level by decreasing $N_2$ formation could not be confirmed. Likewise assumptions that observed high $O_2$ concentrations in the pore water are assumed to restrict $N_2$ formation when nitrate is not limiting denitrification processes due to high atmospheric input (Davidson 1991; Granli and Bøckman 1994, Scholefield et al. 1997) have to be questioned. Denitrification processes resulting in $N_2$ formation in water and sediments require $O_2$ contents of <0.1 to a maximum of 0.8 mg L$^{-1}$ (Granli and Bøckman 1994; Mühlherr and Hiscock 1998; Venterink et al. 2003). Accordingly nitrate should not have been reduced to $N_2$ in large amounts in our slope mire during the study period since the oxygen contents mostly exceeded these values. In addition low pH of the mire pore water should have restricted $N_2$ formation. Acidity inhibits $N_2O$ reductase and thus increases the $N_2O$:$N_2$ ratio (Granli and Bøckman 1994; Aerts 1997). At the prevailing hydro-chemical conditions of our slope mire formation of $N_2O$ should be favoured compared to $N_2$. Various authors reported that groundwater was oversaturated with $N_2O$ which emitted to the atmosphere when the water reached the surface (Mühlherr and Hiscock 1998; Hefting et al. 2006). $N_2O$ captured in groundwaters below our slope mire is likely to be emitted when those groundwaters are rising to the surface in the spring which obviously requires further investigation.

Temporal pattern of $CH_4$ emissions

$CH_4$ fluxes of the mire didn't show any seasonal pattern. Hydro-chemical variables of the mire pore water did not explain fluxes except probably the high $CH_4$ uptake rates of 88 μg m$^{-2}$ h$^{-1}$ at the central part of the mire on the day of 19th June 2002. The high uptake occurred during low water table level of −27 cm and was assumed to be the result of $CH_4$ oxidation by aerobic methanotrophic bacteria when aerobic conditions in peat could be enhanced. Water table has been identified to be the major controlling factor of $CH_4$ emission rates in peatlands. With the water table up to 62% of the variability of $CH_4$ fluxes have been explained (MacDonald et al. 1998; Drösler 2005). Different water table levels have been reported

at which peatlands may change from $CH_4$ release to $CH_4$ uptake. Some authors reported a critical water table level of $>-10$ cm (Christensen et al. 2003; Drösler 2005). In contrast Augustin et al. (1996) observed still small $CH_4$ releases of 0.6–3.5 kg C ha$^{-1}$ year$^{-1}$ in drained mires with water table levels down to $-60$ cm. Beside water table levels plant species composition and cover of vascular plants are known to affect $CH_4$ release from peatlands. Plant species with aerenchymous tissue are able to transport $CH_4$ through the root surface without being oxidized by methanotrophic bacteria (Joabsson and Christensen 2001). Even though these $CH_4$ fluxes would be included in our measurements the mire showed no significant $CH_4$ release. Thus plant mediated $CH_4$ fluxes seems not to be important at the study site although our slope mire show a high cover of vascular plants. Similarly positive impact of available nutrients and labile carbon on the $CH_4$ release (Joabsson and Christensen 2001; Yavitt et al. 2005) could not be confirmed in our study.

Annual $CH_4$ fluxes

Annual $CH_4$ flux revealed an uptake of $-0.02$kg $CH_4$-C ha$^{-1}$ not differing between the forested and non forested parts of the slope mire. The small annual consumption of $CH_4$ is in contrast to reported $CH_4$ releases from peatlands with similar high water table levels (Augustin et al. 1996; Drösler 2005). Restricted oxygen diffusion causing strictly anaerobic conditions of Eh values lower than $-250$ mV and high thickness of peat enhancing anaerobic peat layer capable of $CH_4$ production were discussed to be reasons for high methane fluxes in peatlands with high water table levels (Mitsch and Gosselink 2000). The uptake of $CH_4$ at our slope mire might be the result of a restricted $CH_4$ production due to $O_2$ input through groundwater movement causing redox potential far above the necessary value for methane production. A weak positive correlation between water inflow and oxygen content in pore water ($R=0.52$, $p<0.05$, $n=16$) does indicate the importance of flowing groundwater for methane oxidation in slope mires. An additional explanation for low $CH_4$ emission rates might be the thin peat layer of our slope mire with low total production of methane not exceeding methane oxidation in the aerobic part of the slope mire.

## Conclusions

In contrast to peatlands without permanent water inflow the studied slope mire showed oxygen influx through inflowing pore water restricting reduction processes. Compared to pristine peatlands the influx of oxygen is assumed to restrict $CH_4$ production of the slope mire explaining its weak $CH_4$ consumption. $N_2O$ release from the slope mire didn't differ from those of reported peatlands with high water table levels and low oxygen availability. Nevertheless slope mires have a high potential for the $N_2O$ formation due to available $NO_3^-$. Our assumption that areas of slope mires with springs may be hot spots for $N_2O$ releases requires further research.

## References

Aerts R (1997) Atmospheric nitrogen deposition affects potential denitrification and $N_2O$ emission from peat soils in the Netherlands. Soil Biol Biochem 29:1153–1156

Augustin J, Merbach W, Schmidt W, Reining E (1996) Effect of changing temperature and water table on trace gas emission from minerotrophic mires. Angew Bot 70:45–51

Augustin J, Merbach W, Steffens L, Snelinski B (1998) Nitrous oxide fluxes of disturbed minerotrophic peatlands. Agribiol Res 51:47–57

Brumme R, Borken W, Finke S (1999) Hierarchical control on nitrous oxide emission in forest ecosystems. Glob Biogeochem Cycles 13:1137–1148

Brumme R, Verchot LV, Martikainen PJ, Potter CS (2005) Contribution of trace gases nitrous oxide ($N_2O$) and methane ($CH_4$) to the atmospheric warming balance of forest biomes. In: Griffiths H, Jarvis PG (eds) The carbon balance of forest biomes. Taylor & Francis, Oxon, New York, pp 293–318

Böhlmann N (2004) Wasser- und Stickstoffhaushalt eines soligenen Hangmoores im Hochharz am Beispiel des Ilsemoores. UFZ-Bericht 21, pp 252

Böhlmann N, Meissner R, Bernsdorf S, Böhme F, Russow R, Wegener U (2005) Studies of atmospheric nitrogen deposition in a mire of the German National Park Hochharz Mountains using two different methods. Water Air Soil Pollut 168:17–32

Christensen TR, Ekberg A, Ström L, Mastepanov M (2003) Factors controlling large scale variations in methane emissions from wetlands. Geophys Res Lett 30:1414–1419

Davidson EA (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers JE, Whitman WB (eds) Microbial production and consumption of greenhouse gases: Methane, nitrogene oxides and halomethanes. American Society of microbiology, Washington, pp 219–235

Dorwick DD, Hughes S, Freeman C, Lock MA, Reynolds B, Hudson JA (1999) Nitrous oxide emissions from a gully mire in mid-Wales, UK, under simulated summer drought. Biogeochemistry 44:151–162

Drösler M (2005) Trace gas exchange and climatic relevance of bog ecosystems, Southern Germany. DS thesis, Technical University Munich, Munich, pp 179

FAO/ISRIC/ISSS (1998) World reference base for soil resources. World soil resources report, Vol. 84. FAO, Rome

Granli T, Bøckman OC (1994) Nitrous oxide from agriculture. Norw J Agric Sci 12:1–128

Hefting MM, Bobbink R, Janssens MP (2006) Spatial variation in denitrification and $N_2O$ emission in relation to nitrate removal efficiency in a N-stressed riparian buffer zone. Ecosystems 9:550–563

Heikkinen JEP, Elsakov V, Martikainen PJ (2002) Carbon dioxide and methane dynamics and annual carbon balance in tundra wetland in NE Europe, Russia. Global Biogeochem Cycles 16, DOI 10.1029/2002GB001930

IPCC (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Quin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, pp 212–213

Joabsson A, Christensen TR (2001) Methane emissions from wetlands and their relationship with vascular plants: an arctic example. Glob Chang Biol 7:919–932

Joabsson A, Christensen TR, Wallén B (1999) Vascular plant control on methane emissions from northern peatforming wetlands. Trends Ecol Evol 14:385–388

Khalil MAK (1999) Non-$CO_2$ greenhouse gases in the atmosphere. Annu Rev Energy Environ 24:645–661

Koponen HT, Martikainen PJ (2004) Soil water content and freezing temperature affect freeze–thaw related $N_2O$ production in organic soil. Nutr Cycl Agroecosyst 69:213–219

Koponen HT, Duran CE, Maljanen M, Hytönen J, Martikainen PJ (2006) Temperature responses of NO and $N_2O$ emissions from boreal organic soil. Soil Biol Biochem 38:1779–1787

Loftfield N, Flessa H, Augustin J, Beese F (1997) Automated gas chromatographic system for rapid analysis of the atmospheric trace gases methane, carbon dioxide, and nitrous oxide. J Environ Qual 26:560–564

Macdonald JA, Fowler D, Hargreaves KJ, Skiba U, Leith ID, Murray MB (1998) Methane emission rates from a northern wetland; response to temperature, water table and transport. Atmos Environ 32:3219–3227

Maljanen M, Liikanen A, Silvola J, Martikainen PJ (2003) Nitrous oxide emissions from boreal organic soil under different land-use. Soil Biol Biochem 35:1–12

Martikainen PJ, Nykänen H, Crill P, Silvola J (1993) Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. Nature 366:51–53

Melin J, Nommik H (1983) Denitrification measurements in intact soil cores. Acta Agric Scand 33:145–151

Mitsch JM, Gosselink JG (2000) Wetlands. Wiley, New York, p 920

Moore T, Blodau C, Turunen J, Roulet N, Richard PJH (2004) Patterns of nitrogen and sulfur accumulation and retention in ombrotrophic bogs, eastern Canada. Glob Chang Biol 11:356–367

Mühlherr IH, Hiscock KM (1998) Nitrous oxide production and consumption in British limestone aquifers. J Hydrol 211:126–139

Papen H, Butterbach-Bahl K (1999) 3-year continuous record of N-trace gas fluxes from untreated and limed soil of a N-saturated spruce and beech forest in Germany: I-$N_2O$ emissions. J Geophys Res 104:18487–18503

Regina K, Nykänen H, Silvola J, Martikainen PJ (1996) Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry 35:401–418

Regina K, Syväsalo E, Hannukkala A, Esala M (2004) Fluxes of $N_2O$ from farmed peat soils in Finland. Eur J Soil Sci 55:591–599

Scholefield D, Hawkins JMB, Jackson SM (1997) Use of a flowing helium atmosphere incubation technique to measure the effects of denitrification controls applied to intact cores of a clay soil. Soil Biol Biochem 29:1337–1344

Seitzinger SP (1994) Linkages between organic matter mineralization and denitrification in eight riparian wetlands. Biogeochemistry 25:19–39

Stähli M, Stadler D (1997) Measurement of water solute dynamics in freezing soil columns with time domain reflectometry. J Hydrol 195:352–369

Teepe R, Brumme R, Beese F (2000) Nitrous oxide emissions from frozen soils under agricultural, fallow and forest land. Soil Biol Biogeochem 32:1807–1810

Tokida T, Miyazaki T, Mizoguchi M, Seki K (2005) In situ accumulation of methane bubbles in a natural wetland soil. Eur J Soil Sci 56:389–395

Venterink HO, Hummelink E, Van Den Hoorn MW (2003) Denitrification potential of a river floodplain during flooding with nitrate-rich water: grasslands versus reedbeds. Biogeochemistry 65:233–244

Wegener U, Kison HU (2002) Die Vegetation des Brockens im Nationalpark Hochharz (Exkursion G). Tüxenia 22:243–267

Yavitt JB, Williams CJ, Wieder RK (2005) Soil chemistry versus environmental controls on production of $CH_4$ and $CO_2$ in northern peatlands. Eur J Soil Sci 56:169–178