Biogeosciences, 5, 925–935, 2008
www.biogeosciences.net/5/925/2008/

Biogeosciences

Small scale controls of greenhouse gas release under elevated N deposition rates in a restoring peat bog in NW Germany

S. Glatzel[1], I. Forbrich[2], C. Krüger[3], S. Lemke[3], and G. Gerold[3]

[1]University of Rostock, Faculty for Agricultural and Environmental Sciences, Landscape Ecology and Land Evaluation,
Justus von Liebig Weg 6, 18059 Rostock, Germany
[2]Ernst Moritz Arndt University Greifswald, Institute for Botany and Landscape Ecology, Grimmer Straße 88, 17487
Greifswald, Germany
[3]University of Göttingen, Landscape Ecology Unit, Institute of Geography, Goldschmidtstraße 5, 37077 Göttingen, Germany

Received: 16 November 2007 – Published in Biogeosciences Discuss.: 16 January 2008
Revised: 16 May 2008 – Accepted: 26 May 2008 – Published: 11 June 2008

Abstract. In Central Europe, most bogs have a history of drainage and many of them are currently being restored. Success of restoration as well as greenhouse gas exchange of these bogs is influenced by environmental stress factors as drought and atmospheric nitrogen deposition. We determined the methane and nitrous oxide exchange of sites in the strongly decomposed center and less decomposed edge of the Pietzmoor bog in NW Germany in 2004. Also, we examined the methane and nitrous oxide exchange of mesocosms from the center and edge before, during, and following a drainage experiment as well as carbon dioxide release from disturbed unfertilized and nitrogen fertilized surface peat. In the field, methane fluxes ranged from 0 to 3.8 $\mathrm{mg\,m^{-2}\,h^{-1}}$ and were highest from hollows. Field nitrous oxide fluxes ranged from 0 to 574 $\mu\mathrm{g\,m^{-2}\,h^{-1}}$ and were elevated at the edge. A large *Eriophorum vaginatum* tussock showed decreasing nitrous oxide release as the season progressed. Drainage of mesocosms decreased methane release to 0, even during rewetting. There was a tendency for a decrease of nitrous oxide release during drainage and for an increase in nitrous oxide release during rewetting. Nitrogen fertilization did not increase decomposition of surface peat. Our examinations suggest a competition between vascular vegetation and denitrifiers for excess nitrogen. We also provide evidence that the von Post humification index can be used to explain nitrous oxide release from bogs, if the role of vascular vegetation is also considered. An assessment of the greenhouse gas release from nitrogen saturated restoring bogs needs to take into account elevated release from fresh Sphagnum peat as well as from sedges growing on decomposed peat. Given the high atmospheric nitrogen deposition, restoration will not be able to achieve an oligotrophic ecosystem in the short term.

Correspondence to: S. Glatzel
(stephan.glatzel@uni-rostock.de)

1 Introduction

Due to the high amount of carbon stored in the peatlands of the world and the sensitivity of biogeochemical processes in these ecosystems to climate change, research on matter cycling in peatlands has received considerable interest. Especially the release of greenhouse gases (GHG) as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from peatlands has been the focus of biogeochemical research due to its potential contribution to feedbacks to global warming. Despite large areas of (often degraded) peat bodies in temperate regions, research on peat bogs is mostly from natural boreal sites and focuses on the role of the water table (Roulet et al., 1992; Nykänen et al., 1998; Blodau, 2002).

In temperate Germany, widespread drainage of bogs resulted in a serious decline of peatland area. Today, in NW Germany (Lower Saxony) merely 5% of formerly 2348 $\mathrm{km^2}$ bog area remain undisturbed or in a close to natural state (Schmatzler, 1990). Therefore, protection of the remaining intact peat bogs is accompanied by restoration efforts in moderately degraded bogs. The most important environmental constraints on the successful restoration of these bogs are i) a low water table, a result of previous drainage and climate change, ii) atmospheric N deposition, and iii) strong decomposition of degraded peat.

The importance of water table on GHG release from peat has been discussed extensively (Blodau, 2002). CO_2 evolution follows an optimum function, with highest rates at an intermediate water table (Glatzel et al., 2006). Magnitude and important parameters of CH_4 emission from wetlands are well known (Le Mer and Roger, 2001). Drainage decreases CH_4 release and rewetting does not necessarily lead to an immediate rise in CH_4 release (Tuittila et al., 2000). Jungkunst and Fiedler (2007) stress the role of water table on GHG release and emphasize the climate control on the nature of the relation between water table and GHG release.

Published by Copernicus Publications on behalf of the European Geosciences Union.

Nutrients that may limit decomposition include nitrogen (N) and phosporus (P) (Güsewell and Freeman, 2003). In Lower Saxony, even "undisturbed" bogs are subject to elevated N deposition of up to 70 kg ha^{-1} yr^{-1} (Gauger et al., 2002). At these high N deposition rates, the capacity of *Sphagna* to take up N is exceeded (Lamers et al., 2000), N concentration in pore water accumulates and plants with high N demand as *Molinia caerulea* become more competitive (Limpens et al., 2003). An increasing proportion of easily decomposable litter and N enriched *Sphagnum* tissue enhance decomposition and N mineralization (Lamers et al., 2000; Aerts et al., 1992), facilitating N_2O and CO_2 release. Generally, in bogs, N_2O release is most common in disturbed locations influenced by elevated N content (Regina et al., 1996). N_2O production requires the availability of nitrogen and is highest at high soil moisture, but not inundation (Granli and Bøckmann, 1994).

Decomposition status of peat controls its potential for further decomposition. Examinations by Glatzel et al. (2004) demonstrated a decreasing potential for aerobic and anaerobic CO_2 and CH_4 production with a rising von Post decomposition index. In the Pietzmoor Glatzel et al. (2006) explained increased CO_2 release from *Sphagnum* hollow peat compared to hummock peat by lower decomposition rates of hollow peat. Alm et al. (1999) remarked that increased NO_3 availability may be due to high decomposition, increasing rates of N_2O emission from drained peatlands.

In this contribution we intend to add understanding on the influence of these controls on the GHG release of a restoring temperate bog. Previous investigations (Glatzel et al., 2006) have shown the effect of drought on decomposition rates. Specifically, we investigate the influence of a drawdown in water table and peat properties on methane and nitrous oxide release in a restoring peat bog and the influence of nitrogen on decomposition of surface peat. We hypothesize that i) drought decreases the CH_4 and N_2O release in the bog and rewetting temporarily increases CH_4 and N_2O release, ii) decomposition of peat controls CH_4 and N_2O release, and iii) atmospheric nitrogen deposition accelerates decomposition of surface peat.

2 Site and methods

2.1 Research site

The study site was the Pietzmoor (Lower Saxony; NW, Germany; 53°06′ N; 9°50′ E). It is part of the nature reserve Lüneburger Heide. The bog is located on the eastern edge of the closed occurrence of rainfed bogs in NW Germany. Mean annual precipitation is 790 mm; mean annual temperature is 8°C. The examination period was March to September 2004. Atmospheric N deposition is ca. 22 kg ha^{-1} yr^{-1} (Fottner et al., 2004). Today, the Pietzmoor is moderately degraded. Manual peat extraction at the edges of the Pietzmoor was conducted between the 16th century and 1960. Deep drainage ditches, constructed in the 19th century further degraded the bog, resulting in increased growth of birch (*Betula* sp.) and pine (*Pinus* sp.). Since 1970, when restoration efforts began, drainage ditches have been closed and trees cut. This resulted in formation of a recent superficial acrotelm with *Sphagnum* spp. growing in many hollows. Hummocks are still dominated by *Empetrum nigrum*, *Calluna vulgaris*, and *Eriophorum vaginatum*.

2.2 Field CH_4 and N_2O flux determination

Between March and August 2004, CH_4 and N_2O fluxes were determined 14 times employing a closed chamber method (Hutchinson and Livingston, 1993) at 10 locations within the Pietzmoor bog. Of the 10 previously installed collars (covering 0.068 m^{-2}), five collars were installed in the center and at the edge of the bog. Six collars covered hummocks and four collars covered hollows. Hummocks were 20 cm elevated compared to hollows. They dominate the site resulting in a high coverage of *Calluna vulgaris*, which is typical for dry degraded peatland sites (Rathert, 2004). Due to the protection status of the site it was not possible to construct a system of boardwalks. However, CH_4 fluxes are generally low and we did not find stepwise nonlinear concentration increases in our measurements that would have been a sign for ebullition events (e.g. Chanton and Whiting 1995). Hence, we assume no risk of severe disturbances in our measurement setup.

Among the hollow collars, two were vegetated by *Sphagnum fallax*, one hosted a small *Eriophorum vaginatum* tussock and one contained no living vegetation. Among the hummock collars, three were vegetated by *Calluna vulgaris*, one contained a big and one a small *Eriophorum vaginatum* individuum, and one was inhabited by lichens. These collars covered the range of microsites in the bog previously determined by Rathert (2004).

For gas flux determination, gas samples from the closed chamber were sampled by syringe five times in 5 minute intervals and transported to the laboratory in Göttingen. On the evening of the day of sampling, the 60 mL syringes were attached to an autosampler coupled to a Shimadzu GC-14B gas chromatograph and a set of four different calibration gas cocktails (described by Loftfield et al., 1997). Precision of analysis was 0.4% for CH_4 and 1.0% for N_2O. As no saturation effects were found, fluxes were calculated from the linear slope of the concentration change over time (Lessard et al., 1994) taking into account the headspace temperature and the coefficient of determination for each regression.

2.3 CH_4 and N_2O release from mesocosms

This experiment was set up to test the first hypothesis. Twelve undisturbed peat cores (diameter 15 cm) were sampled by cutting the peat at the outside of tube and simultaneously pushing the tube above the cut peat until average 23 cm of peat were inside the tube. All cores were taken from hollows, six in the center and six from the edge. The peat cores were transferred into 30 cm high mesocosms that enabled sampling of percolating water and gas concentrations from a 7 cm headspace. Peat cores were watered in three day intervals with artificial Schneverdingen rain (diluted ammonium nitrate solution set to a pH of 4.5, equivalent to an amount of 790 mm yr^{-1} and 20 kg dry and wet N deposition ha^{-1} yr^{-1}). As suggested by Blodau et al. (2004), a two month equilibration phase preceded the experiment. During the equilibration phase, the water table was set to 7 cm below ground, which is a compromise between flooded conditions that were found in the hollows and much drier conditions in the hummocks. The cores were stored at 20°C close to windows, allowing a natural night and day regime. Vegetation (*Sphagna* and small herbs, no large plants) continued to grow during the experiment.

The experiment consisted of three phases. The pre-drainage phase preceded the drainage phase. During this phase, the six manipulated cores were subjected to free drainage (restricted to 100 mL d^{-1}) without applying low pressure. At the control cores water table remained close to the peat surface. During the second phase (drainage phase), the manipulated cores were subjected to free drainage. The third phase (post-drainage phase) began by closing the drainage at experimental cores and the daily addition of 40 mL artificial Schneverdingen rain until the water table was back to 7 cm below ground. The pre-drainage phase lasted 5 to 8 days, the drainage phase until the elimination of standing water lasted 5 to 6 days and the regeneration of high water table (post drainage phase) took 12 to 14 days.

During the experiment, we determined gas fluxes from all cores as described above (except for a 30 s sampling interval due to the small headspace) daily. Following the experiment, carbon (C) and N concentration of peat from all cores was determined. This was done by drying peat at 45°C from all horizons, milling it to 0.25 mm and analysis by combustion at 900°C in a LECO CN- Analyzer (LECO, St. Joseph, MI, USA). The C and N concentration of all horizons were averaged to 0–15 cm depth. We also estimated the von Post humification index at all cores. These examinations on peat properties enabled us to test the second hypothesis.

2.4 CO_2 evolution from incubated disturbed samples

In order to test the third hypothesis, we sampled peat from 0–10 cm depth from *Calluna* hummocks and *Sphagnum* hollows in the Pietzmoor. Approximately 20 g of peat were set to 75% water content, which yields intermediate rates of CO_2 evolution (Glatzel et al., 2006) and placed in 400 mL jars in triplicate. All samples were additionally moistened by one mL of liquid. The fertilized samples received 0.036 M ammonium nitrate solution (equivalent to 50 kg N ha^{-1}), and the unfertilized control samples received plain water. The incubation experiment was conducted using the method by Isermeyer (1952) following the experimental design described Glatzel et al. (2006). Briefly, evolved CO_2 was absorbed by 20 mL of 0.1 M NaOH adsorption inside the jars. Sampling of NaOH placed in small containers) following 1, 3, 6, 11, 17, 28 and 42 days of incubation and titration with 0.1 M HCl allows the calculation of CO_2 evolved since the preceding sampling date.

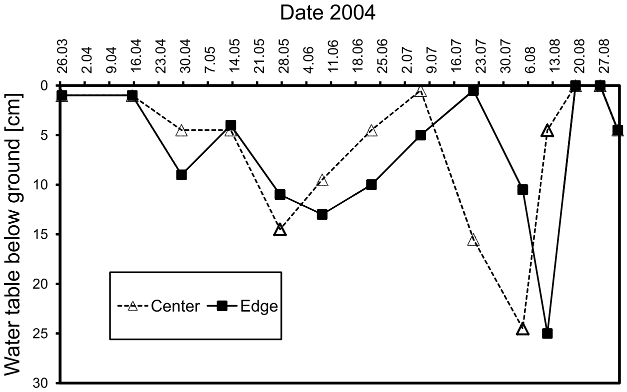

Fig. 1. Water table at the center and at the edge of the research site in the Pietzmoor from March to August 2004.

2.5 Ancillary measurements and statistical procedures

We measured air temperature and precipitation at a weather station located 2 km from the field site and installed an air temperature logger 20 cm above the surface of the bog. We determined water table by previously installed wells at the bog center and edge 14 times between March and August 2004 in hollows at the center and the edge of the Pietzmoor. All data sets were tested for normal distribution using the Kolmogorov-Smirnov test. Data on N_2O release and day of year (Fig. 3) was normal distributed, so Pearson's correlation coefficient was calculated. The other data was generally not normally distributed, and *n* was generally small, so correlation analyses were carried out using Spearman's rho test and differences between data subsets were analyzed using the Wilcoxon test employing the Statistica 6.1 software package (Stat Soft, 2004). The outcome of these tests was the basis for rejection or acceptance of the hypotheses.

3 Results

3.1 Weather and water table

The field season was warmer and wetter than the long term mean (1989 to 2004). Between March and August 2004, we recorded 427 mm precipitation as opposed to a long term mean of 381 mm. Mean temperature during the field season was 14.2°C, compared a long term mean of 13.8°C. At the

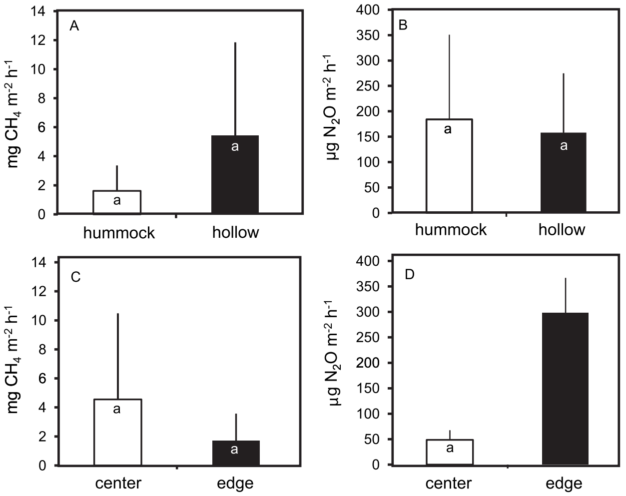

Fig. 2. Methane (CH_4) and nitrous oxide (N_2O) release from hummocks and hollows at the center and the edge of the Pietzmoor, Germany. Shown are means and standard deviations of CH_4 and N_2O release of 14 field gas flux determinations from March to August 2004 (CH_4: **(A)**, N_2O: **(B)**) originating from five center (three hummocks and two hollows) and five edge (also three hummocks and two hollows) locations (CH_4: **(C)**, N_2O: **(D)**). Significantly different values (Wilcoxon test) are marked with different letters.

start of the field season, water table was close to the surface (Fig. 1). Following a rather dry spring, frequent precipitation led to a rise in water table until early July. In July and August, water table dropped to 25 cm, but rose again in late August. In the center of the bog, water table responded more quickly than at the edge.

3.2 Field CH_4 and N_2O fluxes

Field CH_4 fluxes ranged from 0 to 7.8 mg CH_4 m^{-2} h^{-1} and averaged 1.2 mg CH_4 m^{-2} h^{-1}. Spatial variability of CH_4 fluxes was high, so we were not able to detect significant differences between the mean CH_4 flux from hummocks and hollows and between the collars in the center and at the edge of the bog (Fig. 2), although there was a tendency for elevated CH_4 release in hollows and at the center of the bog. As the water table at the center was not lower than at the edge, the absence of a significant difference between CH_4 release at the two sites is not surprising.

Although N_2O fluxes in the field were generally low, and often 0 at some collars, we detected a N_2O release of up to 574 μg m^{-2} h^{-1}. We found no N_2O uptake. There was no difference in N_2O release between hummocks and hollows, but at the edge, nitrous oxide release was higher than at the center (Fig. 1) despite the lack of a difference in water table.

During the course of the season, CH_4 fluxes rose from 0.5 mg m^{-2} h^{-1} to 2 mg m^{-2} h^{-1} (at some hummocks) and 4 to 8 g m^{-2} h^{-1} (at some hollows). This trend could not be noticed at all collars. There was no seasonal trend of N_2O fluxes, except for the collar vegetated by a large *Eriophorum vaginatum* tussock. There, N_2O fluxes decreased linearly with the course of the season (Fig. 3).

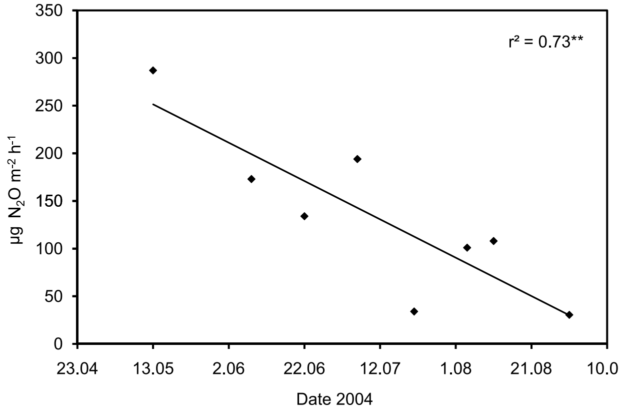

Fig. 3. Nitrous oxide (N_2O) release from an *Eriophorum vaginatum* dominated hummock from April to August 2004 and its relation to sampling date at the edge of the Pietzmoor, Germany (*n*=14).

3.3 CH_4 and N_2O release from mesocosms

3.3.1 Methane

Methane release from the cores was higher than from field sites, averaging 8.2 mg CH_4 m^{-2} h^{-1}. During the pre-drainage phase, there was no difference in CH_4 flux between the control cores and the manipulated cores. During this phase, methane fluxes were between 0.1 and 84.5 mg m^{-2} h^{-1} and averaged 7.6±9.1 to 8.7±11.7 mg CH_4 m^{-2} h^{-1}. (Fig. 4) During drainage, the control cores remained at the CH_4 release level, emitting −0.1 to 138 mg CH_4 m^{-2} h^{-1} and averaging 9.4±11.7 mg CH_4 m^{-2} h^{-1}. Methane release of the manipulated cores dropped to 0 to 3.1 mg CH_4 m^{-2} h^{-1} with a mean release of 0.3±0.4 mg CH_4 m^{-2} h^{-1}. During the third phase, CH_4 emissions from the control plots remained at 0 to 99.6 mg CH_4 m^{-2} h^{-1} with an average value of 8.3±12.9 mg CH_4 m^{-2} h^{-1}. During the post-drainage phase, CH_4 emissions from the manipulated cores remained at the level of the drainage phase emitting 0 to 11.2 mg CH_4 m^{-2} h^{-1} and a mean CH_4 release of 0.3±0.3 mg m^{-2} h^{-1}. In summary, CH_4 release of the manipulated cores remained at close to zero even when the water table reached the original position.

3.3.2 Nitrous oxide

Variability of emissions of N_2O from the cores was higher than the variability of CH_4 emissions. During the first phase, N_2O release from the control cores was 0 to 1571 μg m^{-2} h^{-1} (Fig. 5). Previous to drainage, the manipulated cores released 0 to 2255 μg N_2O m^{-2} h^{-1}. Thus,

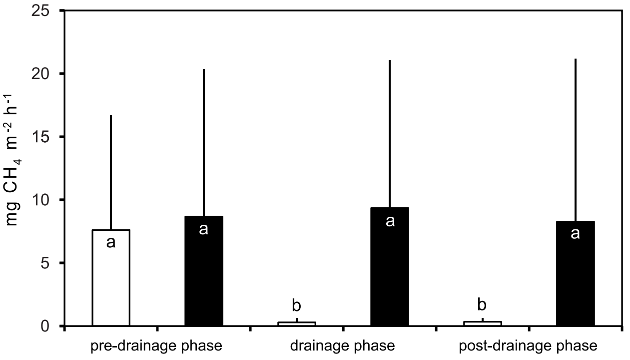

Fig. 4. Methane (CH_4) release from peat cores before, during, and following the drainage experiment (open bars). Unmanipulated control cores are black. Mean values and standard deviation from three replicates are shown. Significantly different values (Wilcoxon test) are marked with different letters.

control cores released 292±361 μg $N_2O\,m^{-2}\,h^{-1}$ opposed to 163±190 μg $N_2O\,m^{-2}\,h^{-1}$ from the manipulated cores, possibly showing an (non significant) effect of beginning drainage. During the drainage phase, N_2O release at manipulated as well as control cores was lower than during the first phase. Due to the higher emission at the manipulated cores during the pre-drainage phase, this change was significant for the manipulated cores in contrast to the control. During this phase, control cores released 0 to 673 μg $N_2O\,m^{-2}\,h^{-1}$ and manipulated cores emitted 0 to 348 μg $N_2O\,m^{-2}\,h^{-1}$. The average values were 75±59 and 73±102 μg $N_2O\,m^{-2}\,h^{-1}$ for the control and the manipulated cores, respectively. During the post-drainage phase, N_2O release from the control cores remained at 0 to 1464 μg $N_2O\,m^{-2}\,h^{-1}$, with an average of 72±69 μg $N_2O\,m^{-2}\,h^{-1}$. The manipulated cores emitted 0 to 1590 μg $N_2O\,m^{-2}\,h^{-1}$, with a mean N_2O release of 150±157 μg $m^{-2}\,h^{-1}$, showing a (non significant) sign of increasing N_2O release. In summary, the extremely high variability and the multiple controls of N_2O release lead to an incoherent emission pattern.

Thus, the mesocosm experiment produced a clear result for CH_4 and no clear result for N_2O. A lasting suppression of CH_4 release during a following drainage is not mirrored by a similar effect for N_2O, although there is a tendency for decreased N_2O release during drainage and possibly a somewhat increased N_2O release following drainage.

3.3.3 Properties of the peat cores

Simple measures of surface peat point towards stronger decomposition of peat in the center of the bog (Table 1): C and N content in the top 15 cm of the peat cores from the center of the bog were significantly higher than from the edge of the bog. There was no significant difference in the C/N ratio from the cores sampled at the center to the ones sampled at the edge of the bog, but cores from the edge tended towards a higher C/N ratio. As evidenced by the von Post index, peat from the bog center was more humified than peat at the bog edge.

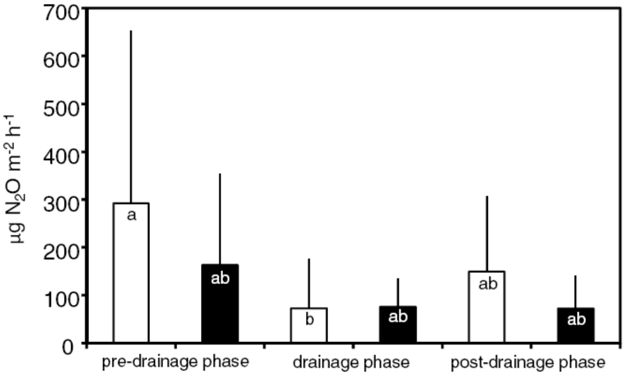

Fig. 5. Nitrous oxide (N_2O) release from peat cores before, during, and following the drainage experiment (open bars). Unmanipulated control cores are black. Mean values and standard deviation from three replicates are shown. Significantly different values (Wilcoxon test) are marked with different letters.

Table 1. Carbon (C) and nitrogen (N) concentration and von Post humification index in the top 15 cm of peat cores used for the water table manipulation experiment from the Pietzmoor, Germany. Mean values and standard deviation from six replicates are shown. Significantly different values (Wilcoxon test) within one line are marked with different letters.

	Center	Edge
	%	
C (%)	48.28±0.69 a	44.10±0.60 b
N (%)	1.59±0.09 a	1.39±0.11 b
	dimensionless	
C/N ratio	30.42±1.54 a	31.92±2.42 a
von Post index	5.3±0.8 a	2.7±0.7 b

3.4 CO_2 evolution from incubated disturbed samples

According to the incubation experiment, N fertilization of surface peat does not control potential CO_2 release. In contrast to sampling depth or peat properties, a wide range of unfertilized and fertilized samples did not differ in the amount of CO_2 release throughout the incubation period. Following 42 days of incubation, unfertilized peat released 43.7±40.1 mg CO_2 per g of dry peat and fertilized peat released 43.0±45.9 mg CO_2 per g of dry peat (Fig. 6).

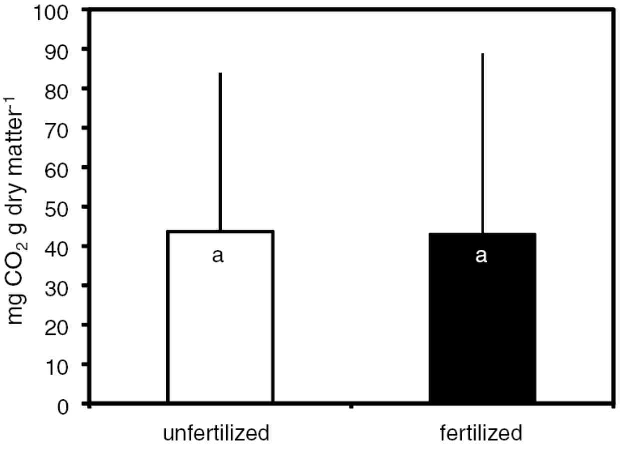

Fig. 6. Carbon dioxide (CO_2) release from unfertilized peat and peat fertilized with ammonium nitrate from the Pietzmoor, Germany, following a 42 day incubation. Mean values and standard deviation from 17 samples are shown. Significantly different values (Wilcoxon test) are marked with different letters.

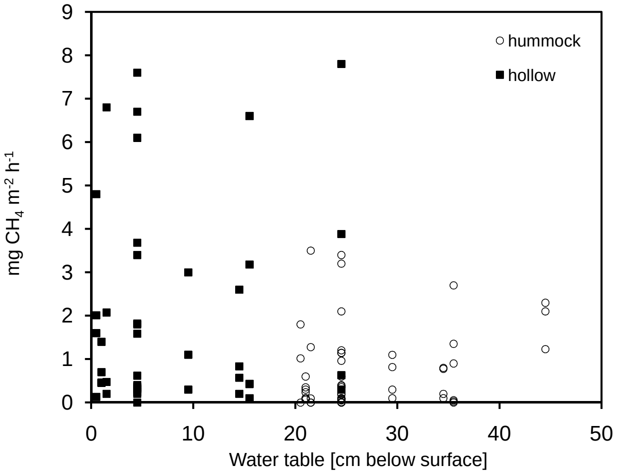

Fig. 7. Methane release and water table from the Pietzmoor, Germany during the 2004 field season. Shown are individual flux determinations from 10 collars and 14 sampling dates from March to August 2004. Water table was corrected for elevation of hummocks by adding 20 cm distance from the bog surface.

4 Discussion

4.1 Field CH_4 and N_2O fluxes

The CH_4 fluxes that we measured in the Pietzmoor are within the range previously reported by many authors and recently reviewed by Le Mer and Roger (2001) and Whalen (2005). Although the high spatial variability of CH_4 fluxes impedes the interpretation of data, we discuss patterns of CH_4 release. The elevated CH_4 emissions from hollows at our sites are probably due to the proximity to the water table and a shallower aerobic zone of CH_4 oxidation (Pelletier et al., 2007; Strack et al., 2004). Furthermore, some of the hollows are covered with *Eriophorum vaginatum*. Vascular plants, especially sedges are known for high CH_4 release (Joabsson et al., 1999; Strack et al. 2006) and *Eriophorum vaginatum* tussocks are CH_4 emission hotspots as they provide substrate for methanogenesis and provide a pathway for CH_4 release (Tuittila et al., 2000; Marinier et al., 2004). The somewhat elevated CH_4 emissions at the center of the bog cannot be explained by water table. However, due to the higher decomposition, field moisture could be higher in the center than at the edge. Only recently, Basiliko et al. (2007) state that mining, alteration and restoration modify the factors controlling CH_4 production, e.g. indicated by a strong influence of soil moisture content on CH_4 production at mined and restored sites while no such correlation could be found at natural sites. In contrast to the hot and dry summer of 2003, the wet summer of 2004 did not cause any drought stress and water table in the center of the bog remained at the same level as at the edge. There was no profound drawdown of the water table. So, water table did not control CH_4 release and the highest CH_4 release ($7.8\,\mathrm{mg\,m^{-2}\,h^{-1}}$) took place on 08/04/04 with the water table at 24.5 cm below the surface (Fig. 7). This is in contrast to the well established relationship between CH_4 release and water table (Moore and Knowles, 1989, Moore and Dalva, 1993) and the idea of water table acting as an "on-off-switch" for CH_4 emissions. The rather steady increase of maximum CH_4 emissions with a rising water table documented in Fig. 7 resembles the relation described by Jauhiainen et al. (2005). In contrast to data from boreal regions cited above, results from temperate regions more frequently do not confirm a straightforward relation between water table and CH_4 release. Fiedler and Sommer (2002) conclude that the effect of water table on CH_4 release in several peatlands of southern Germany is indirect and controlled by more strongly by redox potential, which is rarely determined. Fiedler at al. (2005) state that the thickness of the oxidative zone above the water table does control CH_4 release, but also report CH_4 emission peaks simultaneously to a slightly falling water table.

We are not able to explain the (insignificantly) elevated CH_4 emission in the center of the bog. Following the reasoning of Glatzel et al. (2004), the low degree of humification of surface peat at the edge of the Pietzmoor as evidenced by the von Post index (Table 1) should favor elevated CH_4 emission at that subsite. Consequently, the von Post index is an insufficient measure for CH_4 release. This is not surprising, because this index cannot take into account the function of living plants as *Eriophorum vaginatum* as conduit for CH_4 (Joabbson et al., 1999) and the supply of easily degradable compounds in the rhizosphere of *Eriophorum vaginatum* (Saarnio et al. 2004).

As oligotrophic peatlands are generally N limited, they are usually no sources of N_2O (Martikainen et al., 1993). Thus, the field N_2O fluxes reported in this contribution are high compared with these sites. However it must be taken into account that most studies from pristine oligotrophic peatlands are from boreal sites with rather low atmospheric N deposition (Nordin et al., 1998). Our site has a history of drainage, is located in the temperate zone, experiences high atmospheric N input and a rapid fluctuation in water table (Fig. 1), and, at drought conditions, NO_3-N concentrations of 22±31 mg L^{-1} (Glatzel et al., 2006). The N_2O release from the Pietzmoor is higher than the N_2O release from a restoring peat bog in S Germany, where Drösler (2005) determined an N_2O emission of 1 to 31 μg N_2O m^{-1} h^{-1}. According to our research, only cultivated or drained peatlands release >100 μg N_2O m^{-1} h^{-1}. Regina et al. (1999) measured N_2O release of 440 μg N_2O m^{-1} h^{-1} in a Finnish drained tall sedge fen. On the other hand, the same authors found that rewetting reduces N_2O release from a previously drained birch-pine fen from 50 to 100 μg m^{-1} h^{-1}. Cultivated sites on organic soils from NW Finland released 70 to 170 μg N_2O m^{-1} h^{-1} (Maljanen et al., 2001).

Water table did not control N_2O release (Fig. 8). This is not surprising as the field campaign was rather short and N_2O release is at its maximum in unsaturated soil (Granli and Bøckmann, 1994). Due to the infamously high spatial and temporal variability of soil N_2O emissions (Folorunso and Rolston, 1984), the lack of a difference of N_2O release between hummocks and hollows is not surprising. However, the significantly elevated N_2O release from the edge of the Pietzmoor compared to its center (Fig. 2) is surprising. Even when there is no difference in water table, nitrous oxide flux from the edge of the bog is elevated. Unfortunately, no N data from peat pore water are available from 2004. However, an increased peat pore water NO_3 concentration at the edge of the bog is unlikely: In contrast to the center of the Pietzmoor, NO_3 concentrations in the pore water at its edge never exceeded 0.5 mg L^{-1} between July 2002 and July 2003 (Lemke, 2004). Considering the narrow C/N ratio of surface peat at the center and the edge of the Pietzmoor and the low degree of decomposition at the edge (Table 1), it is possible that the peat itself provided the N source for denitrification. Schiller and Hastie (1996) report N_2O release from the destruction of surface moss following clearfelling, so it is possible that the moss is the N source. This is in line with the findings by Lamers et al. (2000), who found that, at an atmospheric N deposition rate of 12 to 18 kg ha^{-1} yr^{-1}, excess N is accumulated in *Sphagnum* tissue, stored as free N or N-rich free amino acids. Our C/N ratio of 30 is not far from the threshold C/N ratio of 25 for significant N_2O emissions reported by Klemedtsson et al. (2005). In Canadian bogs and the Pietzmoor, Glatzel et al. (2004, 2006) found high CO_2 release rates from poorly decomposed surface Sphagnum peat. Since CO_2 release involves N mobilization and moderately dry conditions are accompanied by the strong CO_2 emissions (Glatzel et al., 2006), in phases of moderate dryness, NO_3 could be accumulated that is subject to denitrification and N_2O release during subsequent wetter phases.

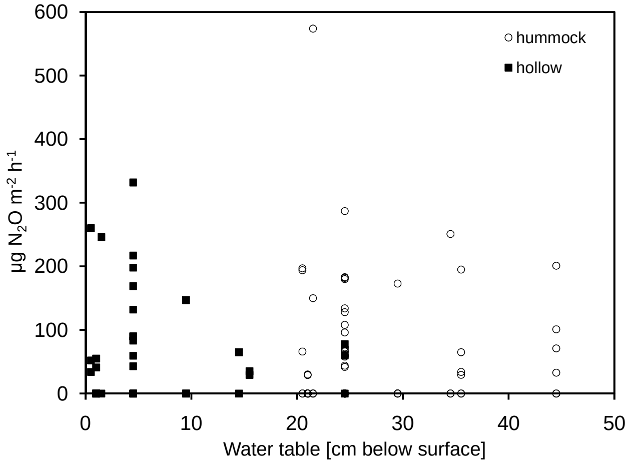

Fig. 8. Nitrous oxide release and water table from the Pietzmoor, Germany during the 2004 field season. Shown are individual flux determinations from 10 collars and 14 sampling dates from March to August 2004. Water table was corrected for elevation of hummocks by adding 20 cm distance from the bog surface.

The decreasing N_2O release from the collar with the large *Eriophorum vaginatum* tussock with the progressing season suggests a competition for excess nitrogen (Silvan et al., 2005). By the end of August, plant uptake of NO_3 keeps N_2O emission close to 0. This mechanism has been noted by Glatzel and Stahr (2001), where it led to soil N_2O uptake. It is interesting that this pattern occurred only where the collar was vegetated by a large cottongrass tussock and suggests effective rhizosperic N uptake. It is likely that the wet summer favored rapid plant uptake of NO_3 as high soil moisture was found to be connected to efficient N uptake of *Phalaris arundinacea* (Rückauf et al., 2004).

4.2 CH_4 and N_2O release from mesocosms

Gas fluxes from mesocosms were higher than from the field. This is due to constantly warm temperatures in the laboratory (Regina et al., 1999) and could, despite the two month equilibration phase, also be a consequence of an enduring disturbance effect following field sampling. As disturbance effects are site specific and there is no standard equilibration period, the comparison of the absolute magnitude of gas fluxes from mesocosms is not useful. Thus, the purpose of CH_4 and N_2O flux determinations from mesocosms is the evaluation of differences between our treatments.

Due to the non-equilibrium conditions caused by the experiment, it is difficult to relate water table to gas fluxes. However, in atlantic temperate climates frequent rainfall and subsequent dry phases are common, so the conditions created by our experiment represent the dynamic conditions encountered in the field.

4.2.1 Methane

The variability of CH_4 fluxes from all mesocosms before drainage and from the control was high, but as a consequence, CH_4 release from the control mesocosms was not different from the mesocosms that were to be manipulated. Our finding that a water table drawdown brings CH_4 release to an end confirms the conclusion by Christensen et al. (2003) that water table acts as an "on-off-switch" for CH_4 emissions. Strack and Waddington (2007) report a more differentiated CH_4 release pattern as a result of water table drawdown. They show that CH_4 release from hummocks may rise following a drawdown due to peat subsidence. CH_4 release following drainage to -50 cm also did not decline to zero (Moore and Dalva, 1993), but the peat columns sampled by Moore and Dalva were 80 cm in length. Our experimental design however eliminated the anoxic zone, – although anoxic pockets may have been preserved –, so differences due to a differing capacity for CH_4 oxidation one might have been able to find in the bog could not be detected. It is still interesting that immediately following the beginning of drainage, CH_4 fluxes at all mesocosms declined to close to 0. Also, CH_4 release did not reappear during the third phase. This confirms findings by Freeman et al. (2002) who reports a suppression of CH_4 for >1 month following a drought and Segers (1998) stated that, due slow growth rates, methanogens require a long regeneration period following exposition to oxygen. So we are not able to report a hysteresis in CH_4 release for the falling and rising limb as detected by Moore and Dalva (1993).

4.2.2 Nitrous oxide

N_2O fluxes from mesocosms declined with drainage, but did not fully recover following drainage. Increasing N_2O release following drainage has been observed in field and laboratory experiments (Freeman et al., 1992, Martikainen et al., 1993, Regina et al., 1999). Dowrick et al. (1999) found that a moderate drought (with a water table at -8 cm) did not affect N_2O released compared to waterlogging and that a more extreme drought (like the one that we simulated) causes an exponential increase in N_2O release with water table depth. On the other hand, Nykänen et al. (2002) determined very low N_2O release rates although the water table subsided up to -40 cm and one site had been fertilized with 100 kg N ha^{-1} prior to the experiment. Nykänen et al. (2002) explain the low N_2O emission despite fertilization with plant uptake and the accumulation of ammonium (NH_4) below the root zone. Another reason for this is probably the low background N load of 6 kg ha^{-1} yr^{-1} and some capacity of the peat for adsorption of NH_4. This is a profound difference to N dynamics of boreal bogs compared to temperate bogs in industrialized regions with high atmospheric N deposition an N loaded peat (Lamers et al., 2000).

There is a (non-significant) rise of N_2O emissions from the manipulated mesocosm in the post-drainage phase. This could be a consequence of nitrification and an accumulation of NO_3 during the drainage phase and denitrification as the water table rises again, explaining the high NO_3 concentration in the pore water of the Pietzmoor during the drought in 2003 (Glatzel et al., 2006). Updegraff et al. (1995) emphasized the relationship between drainage and N mineralization. Regina et al. (1999) elaborate the link between drainage, high NO_3 accumulation and increased N_2O release as well as lower NO_3 concentrations and N_2O release as a consequence of rewetting. Van Beek et al. (2004) concluded that in low-land areas, ground water levels tend to control the magnitude of N losses via denitrification. In summary, although we do not know the reason for the rise of N_2O emissions in the third phase, there is evidence for denitrification following NO_3 accumulation.

4.3 CO_2 evolution from incubated disturbed samples

The purpose of laboratory incubations is the isolation of confounding factors and the absolute values obtained by this type of experiment do not approximate field fluxes. Still, Moore and Dalva (1997) suggested that integrated potential production rates and field fluxes might be similar. In any case, CO_2 productions rates from peats do not differ strongly and can be compared (Glatzel et al., 2004).

The large variability of CO_2 release within the unfertilized and fertilized peat is due to the wide range of peat samples used for the experiment, involving poorly as well as strongly decomposed peat as well as hummock and hollow peat. The absence of any N limitation at optimal peat moisture shows that there is no N limitation of decomposition. Thus, the high N deposition rates in the region do not necessarily directly enhance peat decay, but favor N accumulation in the bog (Lamers et al., 2000). Besides the consequences on CH_4 and N_2O release discussed above, a change in species composition is to be expected in case of persistent high N deposition and drought stress. Specifically, the competitiveness of *Sphagnum* spp. (Lamers et al., 2000, Limpens et al., 2003, Tomassen et al., 2003), *Calluna vulgaris* (Heil and Bruggink, 1987), and *Erica tetralix* (Aerts and Berendse, 1988) suffers facing atmospheric N deposition and N mineralization due to water table subsidence in favor of *Molinia caerulea* (Lamers et al., 2000, Limpens et al., 2003, Tomassen et al., 2003, Heil and Bruggink, 1987, Aerts and Berendse, 1988) and *Betula pubescens* (Tomassen et al., 2003).

5 Conclusions

Our investigations confirm the sensitivity of CH_4 and N_2O fluxes to water table manipulations. However, our examinations show that the water table control is modified by additional factors. Thus, the first part of our first hypothesis –

drought decreases the CH_4 and N_2O release – is accepted. We were not conclusively able to accept the second part of the first hypothesis – rewetting temporarily increases CH_4 and N_2O release.

One of the additional factors that modify the response of CH_4 and N_2O fluxes to water table is the degree of decomposition. We add additional evidence to the notion that the von Post humification index can be used to explain N_2O release, but not CH_4 release from restoring bogs. A large variation of the humification index occurs within small areas. In the strongly decomposed center with scarce *Sphagnum* coverage, N_2O release is lower than at the poorly decomposed edge with fresh N-rich *Sphagnum*. Thus, the second hypothesis, – decomposition controls CH_4 and N_2O release – can be accepted for N_2O, but not for CH_4. CH_4 production appears to be controlled more strongly by plant mediated factors as the CH_4 conduit and root exudates. N_2O emission could be enhanced when N-rich plant tissue is available for decomposition.

Our work also examined the effects of N addition to surface peat and leads to the rejection of the third hypothesis – atmospheric N deposition accelerates the decomposition of surface peat.

The ongoing restoration process in the Pietzmoor aims at the restoration of peatland ecosystems including reestablishment of natural vegetation cover, especially *Sphagnum* mosses, and of the hydrological regime (Rochefort and Lode, 2001). Finally, the return of its functions e.g. accumulation of carbon and nutrient cycling is aspired. Realistically, this is only possible when aiming at developing an eutrophic ecosystem rather than restoring an oligotrophic one.

Another goal of peatland restoration is the net reduction of the release of CO_2 equivalents. This contribution shows that – under conditions of high rates of atmospheric N deposition – it is important to avoid frequent water table fluctuations that may increase N_2O release. Especially in periods when NO_3 uptake by vegetation is not strong (late autumn to early spring), a high water table must be maintained. At this point, we are not able to judge for how long a water table drawdown with subsequent restoration of high water table will decrease CH_4 release. A very low water table may decrease CH_4 and CO_2 efflux, but likely damages peat forming vegetation (Glatzel et al., 2006) and may favor growth of species adapted to a fluctuating water table as *Molinia caerulea*. For this reason, our present state of knowledge suggests that the reduction of the net release of CO_2 equivalents in N loaded temperate peatlands depends on a high water table.

Acknowledgements. The authors are grateful to Dr. J. Prüter and T. Keienburg at the Alfred Töpfer Academy for Nature Conservation in Schneverdingen, Germany and to D. Mertens at the Verein Naturschutzpark in Bispingen, Germany for access to the site and continued support. The thoughtful comments of anonymous referees greatly improved this contribution.

Edited by: T. Laurila

References

Aerts, R., Wallen, B., and Malmer, N.: Growth-limiting nutrients in Sphagnum–dominated bogs, subject to low and high atmospheric nitrogen supply, J. Ecol., 80, 1, 131–140, 1992.

Aerts, R. and Berendse, F.: The effect of increased nutrient availability on vegetation dynamics in wet heathlands Plant Ecology, Vegetatio, 76, 63–69, 1988.

Alm, J., Saarnio, S., Nykänen, H., Silvola, J. and Martikainen, P.: Winter CO_2, CH_4 and N_2O fluxes on some natural and drained boreal peatlands, Biogeochemistry, 44, 2, 163–186, 1999.

Basiliko, N., Blodau, C. P., Bengtson, P. C., Roehm, C., and Moore, T. R.: Regulation of Decomposition and Methane Dynamics across Natural, Commercially Mined, and Restored Northern Peatlands, Ecosystems, 10, 7, 1148–1165, doi:10.1007/s10021-007-9083-2, 2007.

Blodau, C.: Carbon cycling in peatlands - A review of processes and controls, Environ. Rev., 10, 2, 111–134, 2002.

Blodau, C., Basiliko, N. and Moore, T. R.: Carbon turnover in peatland mesocosms exposed to different water table levels, Biogeochemistry, 67, 3, 331–351, 2004.

Chanton, J. P. and Whiting, G. J.: Trace gas exchange in freshwater and coastal marine environments: ebullition and transport by plant, in: Biogenic Trace Gases: Measuring Emissions from Soil and Water,edited by: Matson, P. A. and Harriss, R. C., Blackwell Science, Oxford, 98–125, 1995.

Christensen, T. R., Ekberg. A., Ström, L., Mastepanov, M., Panikov, N., Öquist, M., Svensson, B. H., Nykänen, H., Martikainen, P. J., and Oskarsson, H.: Factors controlling large scale variations in methane emissions from wetlands, Geophys. Res. Lett., 30, 7, 1414, doi:10.1029/2002GL016848, 2003,

Dowrick, D. J., Hughes, S., Freeman, C., Lock, M. A., Reynolds, B., and Hudson, J. A.: Nitrous oxide emissions from a gully mire in mid-Wales, UK, under simulated summer drought, Biogeochemistry, 44, 151–162, 1999.

Drösler, M.: Trace gas exchange and climatic relevance of bog ecosystems, Southern Germany, PhD thesis, Technical University of Munich, 179 pp., http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss20050901-1249431017, 2005.

Fiedler, S. and Sommer, M.: Methane emission from wetland soils in Southwest-Germany, in: Wetlands in Central Europe, edited by: Broll, G., Merbach, W., and Pfeiffer, E.-M., Springer, Berlin, 177–196, 2002

Fiedler, S., Höll, B. S., and Jungkunst, H. F.: Methane budget of a Black Forest spruce ecosystem considering soil pattern, Biogeochemistry, 76, 1, 1–20, 2005.

Folorunso, O. A. and Rolston, D. E.: Spatial variability of field measured denitrification gas fluxes, Soil Sci. Soc. Am. J., 48, 1214–1219, 1984.

Fottner, S., Niemeyer, T., Sieber, M., and Härdtle, W.: Einfluß der Beweidung auf die Nährstoffdynamik von Sandheiden, NNA-Berichte, 17, 80–92, 2004.

Freeman, C., Lock, M. A., and Reynolds, B.: Fluxes of CO_2, CH_4 and N_2O from a Welsh peatland following simulation of water table draw-down: Potential feedback to climatic change, Biogeochemistry, 19, 1, 51–60, 1992.

Freeman, C., Nevison, G. B., Kang, H., Hughes, S., Reynolds, B., and Hudson, J. A.: Contrasted effects of simulated drought on the production and oxidation of methane in a mid-Wales wetland, Soil Biol. Biochem., 34, 61–67, 2002.

Gauger, T., Anshelm, F., and Schuster, H.: Kartierung ökosystembezogener Langzeittrends atmosphärischer Stoffeinträge und Luftschadstoffkonzentrationen in Deutschland und deren Vergleich mit Critical Loads und Critical Levels, UBA Report, FE Nr. 29942210, http://www.umweltdaten.de/luft/ws060207.pdf, 2002.

Glatzel, S. and Stahr, K.: Methane and nitrous oxide exchange in differently fertilised grassland in southern Germany, Plant Soil, 231, 21–35, 2001.

Glatzel, S., Basiliko, N., and Moore, T.: Carbon Dioxide and Methane Production, Potentials of Peats from natural, harvested and restored sites, Eastern Quebec, Canada, Ecoscience, 24, 2, 261–267, 2004.

Glatzel, S., Lemke, S., and Gerold, G.: Short-term effects of an exceptionally hot and dry summer on decomposition in a restoring temperate bog, Eur. J. Soil Biol., 42, 21–22, 2006.

Granli, T. and Bøckmann, O. C.: Nitrous oxide from agriculture, Norw. J. Agr. Sci. S., 12, 1–128, 1994.

Güsewell, S. and Freeman, C.: Enzyme activity during N- and P-limited decomposition of wetland plant litter, B. Geobot. Inst. ETH, 69, 95–106, 2003.

Heil, G. W. and Bruggink, M.: Competition for nutrients between *Calluna vulgaris* (L.) Hull and *Molinia caerulea* (L.) Moench, Oecologia, 73, 105–107, 1987.

Hutchinson, G. L. and Livingston, G. P.: Use of chamber systems to measure trace gas fluxes, in: Agricultural Ecosystem Effects on Trace Gases and Global Change, edited by: Rolston, D. E., ASA Spec. Publ. 55., ASA, CSSA and SSSA, Madison, 63–78, 1993.

Isermeyer, H.: Eine einfache Methode zur Bestimmung der Bodenatmung und der Karbonate im Boden, Z. Pflanzenern. Düng. Bodenk., 56, 26–38, 1952.

Jauhiainen, J., Takahashi, H., Heikkinen, J. E. P., Martikainen, P. J., and Vasander, H.: Carbon fluxes from a tropical peat swamp forest floor, Glob. Change Biol., 11, 1788–1797, 2005.

Joabsson, A., Christensen, T. R., and Wallen, B.: Vascular plant controls on methane emissions from northern peatforming wetlands, Trends Ecol. Evol., 14, 385–387, 1999.

Jungkunst, H. F. and Fiedler, S.: Latitudinal differentiated water table control of CO_2, CH_4 and N_2O fluxes from hydromorphic soils, Glob. Change Biol., 13, 1–16, 2007.

Klemedtsson, L., Von Arnold, K., Weslien, P., and Gundersen, P.: Soil CN ratio as a scalar parameter to predict nitrous oxide emissions, Glob. Change Biol., 11, 1142–1147, 2005.

Lamers, L. P. M., Bobbink, R., and Roelofs, J. G. M.: Natural nitrogen filter fails in polluted raised bogs, Glob. Change Biol., 6, 5, 583–586, 2000.

Le Mer, J. and Roger, P.: Production, emission, and consumption of methane by soils, A review, Eur. J. Soil Biol., 37, 25–50, 2001.

Lemke, S.: Stabilität und Dekomposition des Torfes im wiedervernässten Pietzmoor-Pedoökologische Analysen zum Renaturierungspotential, Diploma Thesis, University of Göttingen, 2004.

Lessard, R. R., Topp, E., Pattey, E., Desjardins, R., and Beaumond, G.: Methane and carbon dioxide fluxes from poorly drained adjacent cultivated and forest sites, Can. J. Soil Sci., 74, 139–146, 1994.

Limpens, J., Berendse, F., and Klees, H.: N deposition affects N availability in interstitial water, growth of *Sphagnum* and invasion of vascular plants in bog vegetation, New Phytol., 157, 339–347, 2003.

Loftfield, N., Brumme, R., and Beese, F.: Automated monitoring of nitrous oxide and carbon dioxide flux from forest soils, Soil Sci. Soc. Am. J., 56, 1147–1150, 1992.

Maljanen, M., Martikainen, P. J., Walden, J. H., and Silvola, J.: CO_2 exchange in an organic field growing barley or grass in eastern Finland, Glob. Change Biol., 7, 679–692, 2001.

Marinier, M., Glatzel, S., and Moore, T. R.: The role of cotton-grass *(Eriophorum vaginatum)* in the exchange of CO_2 and CH_4 at two restored peatlands, Eastern Canada, Ecoscience, 11, 141–149, 2004.

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

Moore, T. R. and Knowles, R.: Influence of Water Table Levels on Methane and Carbon Dioxide Emissions from Peatland Soils, Can. J. Soil Sci., 69, 1, 33–38, 1989.

Moore, T. R. and Dalva, M.: The influence of temperature and water table position on carbon dioxide exchange potentials of peat soils in aerobic and anaerobic laboratory incubations, J. Soil Sci., 44, 651–664, 1993.

Moore, T. R. and Dalva, M.: Methane and carbon dioxide exchange potentials of peat soils in aerobic and anaerobic laboratory incubations, Soil Biol. Biochem., 29, 8, 1157–1164, 1997.

Nordin, A., Näsholm, T., and Ericson, L.: Effects of simulated N deposition on understorey vegetation of a boreal coniferous forest, Funct. Ecology, 12, 4, 691–699, 1998.

Nykänen, H., Alm, J., Silvola, J., Tolonen, K., and Martikainen, P. J.: Methane flux on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates, Global Biogeochem. Cy., 12, 1, 53–69, 1998.

Nykänen, H., Vasander, H., Huttunen, J. T., and Martikainen, P. J.: Effect of experimental nitrogen load on methane and nitrous oxide fluxes on ombrotrophic boreal peatland, Plant Soil, 242, 1, 147–155, 2002.

Pelletier, L., Moore, T. R., Roulet, N. T., Garneau, M., and Beaulieu-Audy, V.: Methane fluxes from three peatlands in the La Grande Riviere watershed, James Bay lowland, Canada, J. Geophys. Res., 112, G01018, doi:10.1029/2006JG000216, 2007.

Rathert, J.: Vegetationsdifferenzierung und Bodeneigenschaften im wiedervernässten Pietzmoor (NSG Lüneburger Heide), Diploma Thesis, University of Göttingen, Göttingen, 2004.

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

Regina, K., Silvola, J., and Martikainen, J.: Short-term effects of changing water table on N_2O fluxes from peat monoliths from natural and drained boreal peatlands, Glob. Change Biol., 5, 183–189, 1999.

Rochefort, L. and Lode, E.: Restoration of degraded boreal peatlands, in: Boreal Peatland Ecosystems, edited by: Wieder, R. K. and Vitt, D. H., Springer, Berlin, Heidelberg, New York, 2001.

Roulet, N., Moore, T., Bubier, J., and Lafleur, P.: Northern fens: methane flux and climatic change, Tellus B, 44, 2, 100–105, 1992.

Rückauf, U., Augustin, J., Russow, R., and Merbach, W.: Nitrate removal from drained and reflooded fen soil affected by soil N transformation processes and plant uptake, Soil Biol. Biochem., 36, 77–90, 2004.

Saarnio, S., Wittenmayer, L., and Merbach, W.: Rhizospheric exudation of *Eriophorum vaginatum* L. – potential link to methanogenesis, Plant Soil, 267, 343–355, 2004.

Schiller, C. L. and Hastie, D. R.: Nitrous oxide and methane fluxes from perturbed and unperturbed boreal forest sites in northern Ontario, J. Geophys. Res.-Atmos., 101, 22 767–22 774, 1996.

Segers, R.: Methane production and methane consumption: A review of processes underlying wetland methane fluxes, Biogeochemistry, 41, 23–51, 1998.

Silvan, N., Tuittila, E. S., Kitunen, V., Vasander, H., and Laine, J.: Nitrate uptake by Eriophorum vaginatum controls N_2O production in a restored peatland, Soil Biol. Biochem., 37, 1519–1526, 2005.

Schmatzler, E.: Die niedersächsischen Hochmoore in ihrer Bedeutung für den Naturschutz, Moor und Tor in Niedersachsen, 5, 49–58, 1990.

StatSoft, Inc.: STATISTICA für Windows, Version 6, www.statsoft.com, 2004.

Strack, M., Waddington, J. M., and Tuittila, E. S.: Effect of water table drawdown on northern peatland methane dynamics: Implications for climate change, Global Biochem. Cy., 18, GB4003, doi:10.1029/2003GB002209, 2004.

Strack, M., Waller, M. F., and Waddington, J. M.: Sedge succession and peatland methane dynamics: A potential feedback to climate change, Ecosystems, 9, 278–287, 2006.

Strack, M. and Waddington, J. M.: Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment, Global Biogeochem. Cy., 21, 1, GB1007, doi:10.1029/2006GB002715, 2007.

Tomassen, H. B. M., Smolders, A. J. P., Lamers, P. M., and Roelofs, J. G. M.: Stimulated growth of Betula pubescens and Molinia caerulea on ombrotrophic bogs: role of high levels of atmospheric nitrogen deposition, J. Ecol., 91, 375–370, 2003.

Tuittila, E.-S., Komulainen, V.-M., Vasander, H., Nykänen, H., Martikainen, P. J., and Laine, J.: Methane dynamics of a restored cut-away peatland, Glob. Change Biol., 6, 569–581, 2000.

Updegraff, K., Pastor, J., Bridgham, S. D., and Johnston, C. A.: Environmental and Substrate Controls over Carbon and Nitrogen Mineralization in Northern Wetlands, Ecol. Appl., 5, 151–163, 1995.

Van Beek, C. L., Hummelink, E. W. J., Velthof, G. L., and Oenema, O.: Denitrification rates in relation to groundwater level in a peat soil under grassland, Biol. Fertil. Soils, 39, 329–336, 2004.

Whalen, S. C.: Biogeochemistry of Methane Exchange between Natural Wetlands and the Atmosphere, Environ. Eng. Sci., 22, 1, 73–94, 2005.