Chapter 18
N_2O Emission from Temperate Beech Forest Soils

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18.1 Introduction

The interest on N_2O emission has increased since the late 1980s after realizing that N_2O is an important greenhouse gas (Lashof and Ahuja 1990; Bouwman 1990a) which destroys ozone in the stratosphere by catalytic reactions (Crutzen 1970). The high global warming potential (GWP) of N_2O has increased the scientific research effort on assessing N_2O fluxes from soils of terrestrial ecosystems (Andreae and Schimel 1989; Bouwman 1990a; Granli and Bøckman 1994) because soils are the largest natural source of N_2O (IPCC 2001). Studies in the 1980s suggested that tropical forests are larger sources for N_2O than temperate and boreal forests, whereas recent studies have indicated that beech (*Fagus Sylvatica* L.) forests can have N_2O fluxes similar to those observed in tropical forests (Brumme and Beese 1992; Papen and Butterbach-Bahl 1999; Zechmeister-Boltenstern et al. 2002). Beech forests with high annual N_2O fluxes have a seasonal emission pattern with high N_2O fluxes in summer and low N_2O fluxes in winter. However, most temperate forests (beech, spruce, oak) have low background N_2O emissions during the year which lack any seasonal trend (Brumme et al. 1999). There are some questions which need to be answered to understand the importance of forests with a seasonal emission pattern for the global balance of N_2O (Brumme et al. 2005). In this chapter, temporal and spatial variations of N_2O emissions from a beech forest ecosystem with a seasonal emission pattern will be provided, leading to a discussion on the mechanisms and processes responsible for seasonal and background patterns of N_2O emissions. Attempts will be made to assess the effect of temperature change, forest management practices (harvesting, liming, soil compaction), and nitrogen inputs on N_2O emissions.

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18.2 Method

To study the *temporal and spatial variation* of N_2O emissions we used 25 static, double-walled, closed chambers which had 12 cm inside diameter and were surrounded by a buffer zone to prevent wind effects as reported by Matthias et al. (1980). The outside diameter of the chamber was 25 cm. Thirty measurements from May 1991 to September 1991 were taken at the B2 plot at the Solling site (about 500 m from the long-term monitoring plot B1). Five subplots (1 × 1 m), each with five closed chambers, were established. The subplots were located in the middle and at the corners of a 60 × 60 m plot. This experimental design allowed us to study the small- and large-scale spatial variations of N_2O emissions. After gas measurements, the surface organic layer and 0–5 cm of the mineral soil under each chamber were collected and analyzed for the weight of different layers, fine root mass, the C and N contents, and the C/N ratios. To study the *N_2O emissions from beech forests* large ($0.25\ m^2$) closed chambers ($n = 3$) were installed for gas measurements at the Göttinger Wald and Zierenberg sites, and on the following different plots at the Solling site: the control plot (long-term trace gas plot B1), the limed plot (BK, 30 tons of dolomitic limestone applied in 1982; see site description in Chap. 3), and the fertilized plot (BN, 140 kg N ha^{-1} applied annually from 1983 to 1993 as $(NH_4)_2SO_4$; see site descriptions in Chap. 3).

Effects of forest management on N_2O emissions were studied in a limed (3 tons ha^{-1} dolomite applied in autumn 1989) and an unlimed forest gap (30 m in diameter, established in autumn 1989) in the B2 plot at the Solling site. Another gap was established at the Zierenberg site in autumn 1990. Gas samples were taken between January and December 1994 at the Solling site and from June 1991 to June 1992 at the Zierenberg site with three closed chambers at each site using evacuated glass bottles (100 mL) and an automatic gas chromatograph (Loftfield et al. 1997).

18.3 Temporal Variation of N_2O Emission

Diurnal changes in soil temperature affected N_2O emissions much more strongly than soil respiration (Chap. 17). A daily increase in soil temperature between 0.2 and 2°C increased N_2O emissions by 10–470% as measured with automatic chambers in August 1988 at the B1 plot (Solling) (Brumme and Beese 1992). In order to find the most suitable time to take measurements during the day that would avoid diurnal variations, 700 measurements (five measurements per day) were taken during 140 days in each of nine chambers, and compared with the measurements taken during 0630 and 1130 hours once a week (30 measurements at each chamber taken during 140 days). One time gas samples taken between 0630 and 1130 hours showed an overestimation of N_2O emissions by values of +3% and +49% in single chambers with a mean increase of +21%. Similar results were obtained by Smith and Dobbie (2001) who used an automated system that provided flux data at 8-h intervals when compared with manual sampling conducted at intervals of 3–7 days. Integrated flux values based on the more intensive measurements were on average no more than

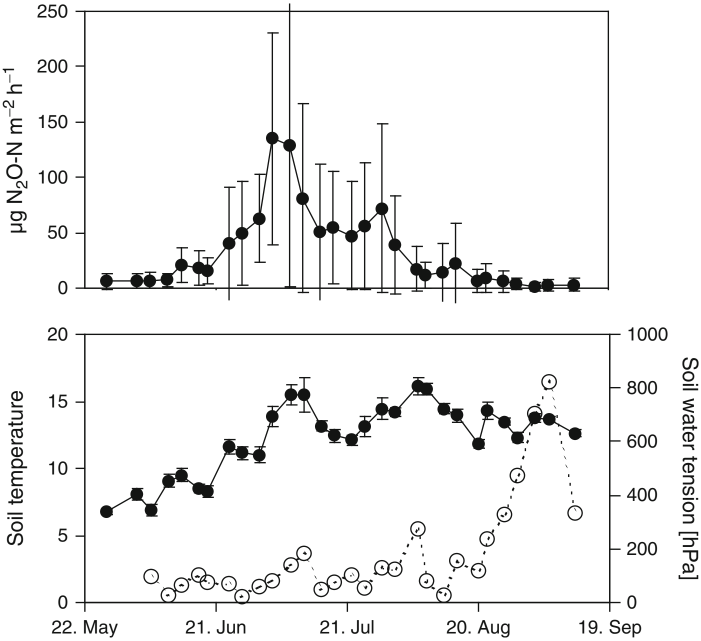

Fig. 18.1 Seasonal variation of N_2O emission rates ($n = 25$), soil temperature (*filled circle*) (5 cm depth) and soil water tension (*open circle*) (hPa) (5 cm below surface organic layer) and standard deviation from May to September 1991 at Solling on the B2 plot

14% greater than those based on manual sampling. However, Flessa et al. (2002) showed that fluxes could be underestimated by less intensive measurements during short periods of extremely high N_2O emissions as would occur during frost–thaw cycles.

The seasonal variations of N_2O emissions were pronounced at the Solling beech site (Fig. 18.1) and were observed since the measurements started in 1987 (Loftfield et al. 1992; Brumme and Beese 1992; Brumme 1995). Temperatures of >10°C increased the N_2O emissions which resulted in high summer fluxes until the soil dried with water tension values exceeding 200 hPa (Figs. 18.1, 18.7). Low precipitation in the summer months therefore resulted in high water tensions and low annual fluxes of N_2O emissions, in contrast to those years when summer precipitation was high, as shown for the years 1994 and 1993 in Fig. 18.8.

At the Göttinger Wald and Zierenberg sites, a low background emission pattern of N_2O emissions was measured during the year and the seasonal emission pattern was lacking. The emission values did not exceed 15 µg N m^{-2} h^{-1} at the Göttinger Wald site and 30 µg N m^{-2} h^{-1} at the Zierenberg site. Seasonal emission patterns were often observed in beech forests with moder humus, whereas the background emission patterns occurred in those with mull humus (Brumme et al. 1999). High rates of N_2O emissions were observed during short periods of freezing–thawing cycles in all forests whether they showed seasonal emission pattern or background emission pattern.

18.4 Spatial Variation of N_2O Emissions

The spatial variation, expressed as the coefficient of variation (cv) of mean N_2O emissions of 25 chambers in a 60 × 60 m plot, ranged from 64 to 228% with a mean value of 119% for 30 sampling dates at the Solling site. Values of coefficient of variation of <125% occurred in spring and summer months and those of >125% in autumn months indicating primarily the irregular spatial changes in soil moisture content in autumn. A lower cv value for N_2O emission was found within the five 1 × 1 m subplots (35–101%, mean 59%) and between the five 1 × 1 m subplots (49%).

Mean N_2O emissions of the 25 chambers within the 60 × 60 m plot correlated significantly with the fine root mass (Fig. 18.2). With increasing fine root biomass from 0.2 to 3.7 g per chamber N_2O emission decreased from 2.5 to 0.1 kg N ha^{-1} per 107 days. A higher root density reduced the water and nitrate concentration and increased the oxygen consumption. There is, however, an interaction between a lowering of water content and an increase in the oxygen diffusivity. In this case, the reduction of N_2O emission indicated that the higher oxygen demand of roots was overcompensated by higher oxygen diffusivity. Nitrate concentration was probably not the limiting factor in this high N soil. Within the five subplots where small scale variation was measured, the mean N_2O emissions correlated significantly with the moisture content at three subplots (R^2 = 0.47, 0.54, 0.97) and with the C content (R^2 = 0.67) at one subplot.

18.5 Landscape Control on N_2O Emissions

Annual value of N_2O emission at the beech forest at the Solling B1 plot was 1.92 kg N ha^{-1} per year for a 10-year measuring period (1995–2000) (Table 18.1). This N_2O emission rate was three and eight times higher than at the Zierenberg and Göttinger Wald sites where amounts of 0.41 and 0.16 kg N ha^{-1} per year were recorded, respectively.

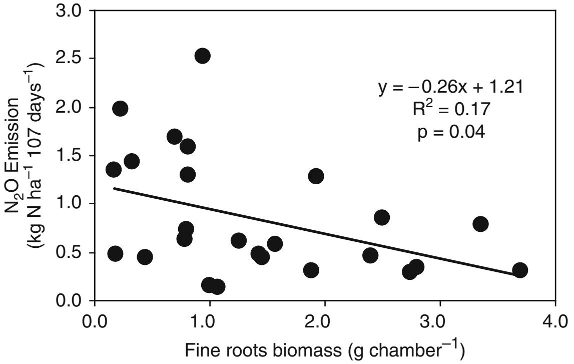

Fig. 18.2 Relationship between cumulative values of N_2O emission for 107 days and fine root biomass (O-horizon and 0–5 cm depth per chamber) within an 60 × 60 m of the B2 plot at Solling

Table 18.1 N_2O emission (kg N ha^{-1} per year) at Göttinger Wald, at the main research area at Zierenberg (ZB1) and at a control and harvested site at Zierenberg (ZB2 control and ZB2 gap), at Solling (B1, B2 sites) and for a fertilized (BN) and limed plots (BK) adjacent to B1 and a gap and limed gap adjacent to B2 at Solling site (standard deviation values in parenthesis)

Site	Plot	Sampling dates	Period	N_2O emissions
Solling	B1, control	319	1990–2000	1.92 (0.63)
	BN, fertilized	72	1993–1995	2.91 (0.90)
	BK, limed	71	1993–1995	0.41 (0.16)
	B2, control	55	1994	1.34 (0.30)
	B2, gap	55	1994	4.19 (1.28)
	B2, limed gap	55	1994	3.29 (1.98)
Göttinger Wald		63	1993–1995	0.16 (0.002)
Zierenberg	ZB1	23	1991–1992	0.41 (0.12)
	ZB2, control	23	1991–1992	0.39 (0.08)
	ZB2, gap	23	1991–1992	0.27 (0.13)

A literature review by Brumme et al. (1999) indicated that only 5 of 29 forests in the temperate biome where whole-year N_2O emissions measurements were carried out, showed high seasonal emission pattern with annual emission rates of >1 kg N ha^{-1} per year. One key factor responsible for high seasonal emission pattern values was the low air diffusivity causing reducing conditions in soils. At the beech forest at the Solling site, low diffusivity values were observed in the surface organic layer and the mineral soil as compared to the Göttinger Wald site (Fig. 18.3). The broad leaves of beech litter are often tightly packed on the surface of a moder type humus causing long diffusion pathways for oxygen (Fig. 18.4). When air diffusivity of the surface organic layer at the beech site was compared with that on the spruce site (both sites have moder form of humus, but the Solling spruce site had low background emissions), the values were about 70% lower at the beech site (Ball et al. 1997). A litter fall exchange experiment at the Solling site, where litter falls at the beech and spruce stands were collected above the gas chambers and replaced across the sites, revealed the importance of different structure of tree litter for N_2O emissions (Brumme et al. 1999). The N_2O emission decreased at the beech stand and increased at the spruce site during the following 3–4 years of the experiment.

Low air diffusivity in the mineral soil layers caused by temporary water-logged soil is another important factor at the ecosystem level. Permanently water-logged soils (Histosol) are low sources of N_2O while a drained site showed very high losses (Brumme et al. 1999). A study on well-drained *Cambisols* and water-logged *Gleysols* and *Histosols* showed the following ranges in N_2O emission: from 0.3–0.8 kg N ha^{-1} per year (*Cambisols*), 1.4–2.7 kg N ha^{-1} per year (*Gleysols*), and 3.7–4 kg N ha^{-1} per year (*Histosols*) of a Norway spruce stand in Germany (Jungkunst et al. 2004; Lamers et al. 2007).

In a majority (21 out of 29) of forests where whole-year measurements of N_2O emissions were made, low background emission patterns of < 1 kg N ha^{-1} per year with a mean of 0.39 ± 0.27 kg N ha^{-1} per year were reported (Brumme et al. 1999).

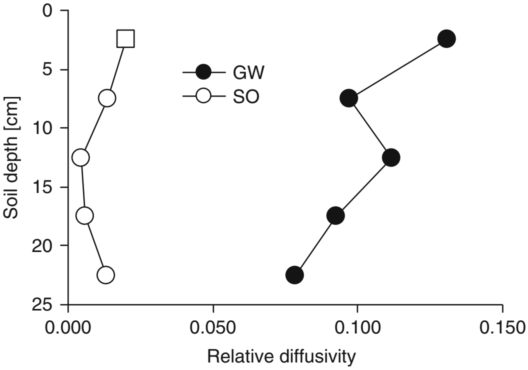

Fig. 18.3 Relative diffusivity (diffusivity in the soil related to diffusivity in air) in different soil depths at the beech sites Göttinger Wald (*GW*) and Solling (*SO*) (Ball et al. 1997) (the *square* for the *SO* site indicates the relative diffusivity in the moder humus)

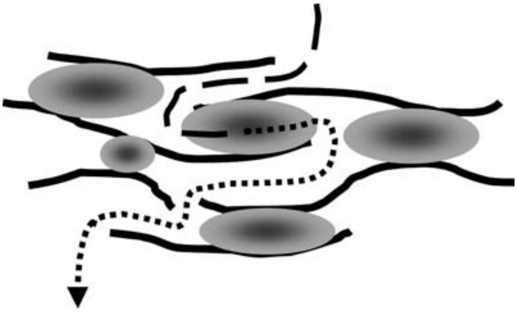

Fig. 18.4 Diffusion pathway of oxygen around beech leaves in the air and water-filled (*ellipsis*) pore spaces of a moder type humus

Similar values (0.34 ± 0.21 kg N ha^{-1} per year, $n = 10$) were calculated for beech forests with background emission pattern of N_2O with values ranging from 0 to 0.9 kg N ha^{-1} per year. Coniferous forests with moder type humus and deciduous forests with mull type humus in most cases show this type of background emission pattern. Mull type humus soils are common for base rich soils like Göttinger Wald or Zierenberg. These soils showed a high earthworm activity (Chap. 7) which created better air diffusivity conditions by preventing litter accumulation on the surface of the mineral soils, and by creating a high proportion of macro pores in deeper soil layers (Fig. 18.3). Most of these sites with background emission pattern of N_2O showed that emissions increased with increasing C content of the surface organic layer (Fig. 18.5). Hence, the thickness of the surface organic layer could serve as a simple indicator for the magnitude of N_2O emissions in deciduous forest ecosystems, and was used to produce a regional-based estimate of N_2O emissions from German forests (Schulte-Bisping et al. 2003). Mean annual emission of 0.32 kg N ha^{-1} per year from German forest soils was calculated after stratifying forests in to seasonal emission type (2.0 kg N ha^{-1} per year) and background emission types (deciduous: 0.37 kg N ha^{-1} per year; conifers: 0.17 kg N ha^{-1} per year). With

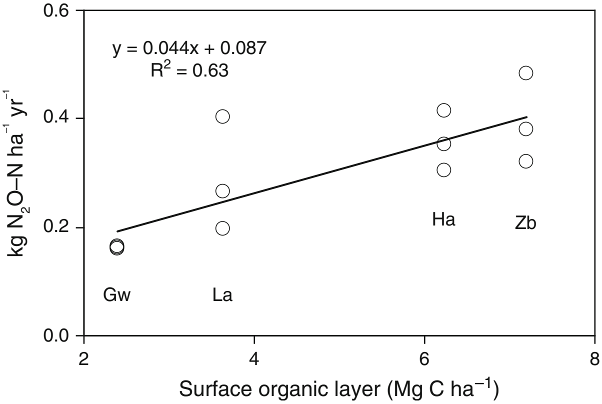

Fig. 18.5 Relationship between background emission pattern of N_2O ($n = 3$) and C-amount in the surface organic layer of four beech forests (*Gw* Göttinger Wald, *Zb* Zierenberg; for *Ha* Harste and *La* Lappwald, from Brumme et al. 1999)

this approach, the emissions from forests in the temperate biome were estimated to be 0.43 kg N ha^{-1} per year (Brumme et al. 2005). However, the results from a process-oriented model (PnET-N-DNDC) by Butterbach-Bahl et al. (2001, 2004), which was validated for a forest site with seasonal emission pattern, has resulted in much higher emission rates for southern Germany and Saxony with values of approximately 2 kg N ha^{-1} per year. This estimate was questioned by Kesik et al. (2005) using a new version of PnET-N-DNDC for calculating the European inventory of N_2O and NO for forest soils. The source strength for German forest soils was considerably lower and amounted to 0.7 kg N ha^{-1} per year.

Field studies with ^{15}N labelled nitrate and ammonium indicated that denitrification was the main source of high seasonal N_2O emissions at Solling (Wolf and Brumme 2002). However, in spring or autumn, heterotrophic nitrification may be involved. In laboratory experiments where high soil moisture conditions (100% WHC) and high nitrate concentrations were maintained, high N_2O emissions were observed for the Göttinger Wald soil. This soil usually had low emissions under field conditions, indicating that the laboratory conditions increased the N_2O emissions up to the level of seasonal emission pattern (Wolf and Brumme 2003). Similar experiments which were carried out with ^{15}N enrichment in nitrate and N_2O indicated that denitrification was the primary process responsible for the formation of N_2O at the Göttinger Wald site. This leads us to hypothesize that high seasonal emissions of N_2O are derived from denitrification, and low background emissions may probably be associated with heterotrophic nitrification. The dominance of denitrification for N_2O formation in forest soils was also suggested by a laboratory study on undisturbed soil cores from 11 forests in Europe (Ambus et al. 2006). In this study, nitrate was the dominant substrate for N_2O with an average contribution of 62% to N_2O formation.

18.6 Relationship Between Temperature and N_2O Emission

Forests with seasonal emission pattern of N_2O showed a high temperature sensitivity for N_2O (Q_{10} value of 9.0; Fig. 18.6, Table 18.2). Low values of soil moisture contents (soil water tensions of >200 hPa) reduced the temperature sensitivity of N_2O emissions (Fig. 18.6) and were excluded from the calculation. High Q_{10} values of N_2O emission of up to 14 have been observed at a forest gap at the Solling site where emissions were not restricted by low soil moisture content (Brumme 1995). A high temperature response (Q_{10} = 6.5) was observed at the beech forest at Höglwald, Germany, a site with seasonal emission pattern of N_2O (Papen and Butterbach-Bahl 1999). At forests with background emission pattern of N_2O, for example at the Göttinger Wald site, N_2O emissions were not affected by soil temperature. However, at the Zierenberg site, a small temperature response of N_2O emissions were observed. Fertilization decreased the temperature sensitivity (Q_{10} of 6.8) as compared to the control plot, and liming drastically reduced the N_2O emissions lowering the temperature response to a value of zero. The literature

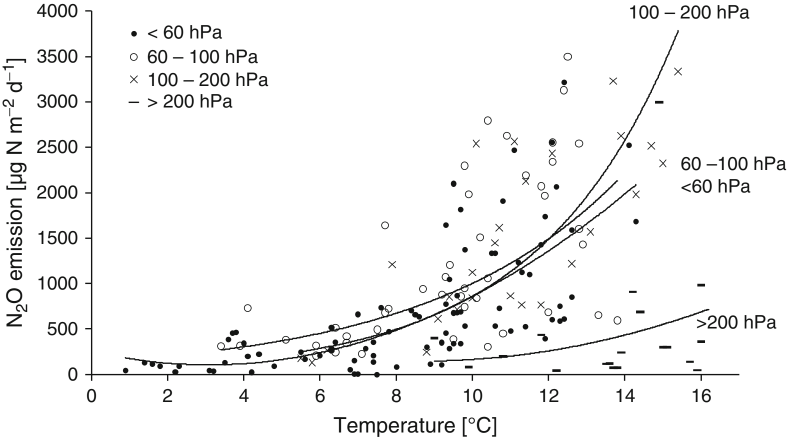

Fig. 18.6 Nitrous oxide emissions with changes in soil temperature (5 cm depth) and soil water tension (hPa) (5 cm below surface organic layer) at the Solling B1 plot (n = 3) during 1991–2000

Table 18.2 Temperature sensitivity expressed as apparent Q_{10} values of N_2O emissions at Göttinger Wald, Zierenberg, and Solling (control B1, limed BK, and fertilized BN) sites

Site	Plot	Treatment	Q_{10}
Solling	B1	Control	9.0
	BK	Limed	0
	BN	Fertilized	6.8
Göttinger Wald			0
Zierenberg			1.5

reviews by Smith (1997) and Granli and Bøckman (1994) showed that high Q_{10} values of N_2O emission have often been reported. The rule of vant't Hoff means that temperature normally doubles biological reaction by a temperature increase of 10°C ($Q_{10} = 2$). Q_{10} values greater than 2–3 indicate that additional to temperature positive feedback mechanisms are involved (Brumme 1995). High temperatures increase the oxygen consumption by micro-organisms, roots, and mycorrhizae and reduce the oxygen concentration in soils under conditions of low oxygen supply. Root detritus and exudates may increase with temperature exerting a positive feedback effect on N_2O emissions. Partially anoxic conditions in soil aggregates usually increase exponentially because of a strong nonlinear increase of anaerobic soil volume in soil aggregates with temperature, and would result in high Q_{10} (Smith 1997) values even under laboratory conditions without the positive feedback mechanisms by roots. We conclude that reliable assessment of the temperature sensitivity of the emission of N_2O is hardly possible since the oxygen availability, the most important regulator for the production of N_2O, changed with temperature. Thus, the values presented for the temperature sensitivity of N_2O emission are apparent Q_{10} values and reflect the temperature response of the whole ecosystem.

18.7 Implications of Forest Management for N_2O Emissions

Thinning and harvesting practices in forests usually reduce root content and may increase soil temperature, soil moisture, nitrate concentrations, and radiation of the surface organic layer (Likens and Bormann 1995; Bauhus and Bartsch 1995), causing an increase in N_2O emissions. Measurements with a full automatic chamber system on a transect from the center of a forest gap (30 m diameter; see Bartsch et al. 2002) to the stand at the Solling site (B2 plot) showed that seasonal N_2O emissions were higher in the gap and existed for a prolonged period in the summer and autumn months of 1991 (1.5 years after clearing; Brumme 1995). The effect of harvesting continued at least up to 1994 (4.5 years after clearing) as indicated in Fig. 18.7. On an annual basis, N_2O emissions increased by 460% in 1991 and by 220% in 1994 in the center of the gap compared to the stand. A temperature effect was not observed because of shading by the surrounding trees. The surface organic layer was not covered by ground vegetation before harvesting and the removal of trees did not effect the growth in 1991 (Bartsch et al. 2002). In 1994, only 20% of the land surface was covered by ground vegetation. Consequently, soil water tension did not exceed 200 hPa and nitrate concentration was several times higher than on the control plot and may have caused the high N_2O emissions in the gap.

In contrast to the Solling site, harvesting did not affect N_2O emission at the Zierenberg site (Table 18.1). The ground vegetation grew back quickly after harvesting (Godt 2002) which probably reduced soil moisture levels and nitrate concentration. Similar results were shown by Dannenmann et al. (2007) in a thinning study in three beech forests on calcareous soils covered with mull type humus. One of three forests in that trial showed increased N_2O emission in the first

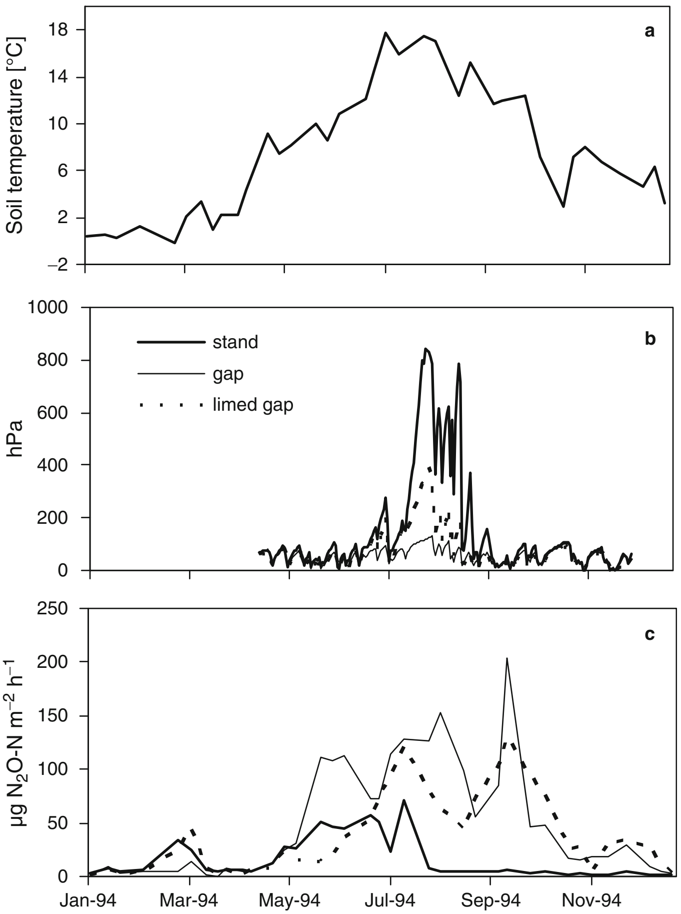

Fig. 18.7 Soil temperature in the OH layer (**a**), soil water tension (hPa) at 10 cm soil depth (**b**), and N_2O emission (µg N m^{-2} h^{-1}) at the Solling control plot B2 and a adjacent limed gap and a control gap (**c**) for January to December 1994

two summers after thinning and declined in the third year, which was accompanied by the development of understorey vegetation.

Nitrate is one of the most important controlling factors affecting N_2O emissions from agricultural soils (Bouwman 1990b) whereas it is of less importance on forest land (Schmidt et al. 1988; Bowden et al. 1991; Mogge et al. 1998; Brumme et al. 1999; Papen and Butterbach-Bahl 1999; Ambus and Robertson 2006). A fertilizer experiment at the Solling site (BN plot) confirmed this result. After fertilization, the mean nitrate concentration was 20 mg N L^{-1} in contrast to 0.7 mg N L^{-1} at the control B1 plot while the emission of N_2O amounted to 2.9 kg N ha^{-1} per year (Fig. 18.8, Table 18.1) and was not significantly higher than observed for the same period at the control plot (2.3 kg N ha^{-1} per year, SD 0.57). The differences between forest and agricultural land are probably related to high nitrification rates

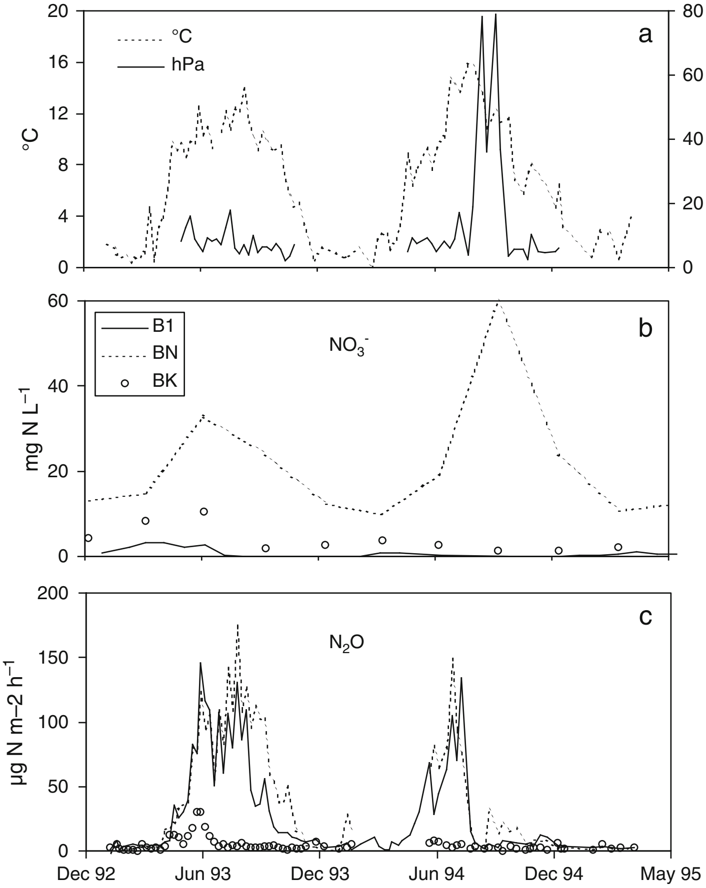

Fig. 18.8 Soil temperature in the H layer and soil water tension at 10 cm soil depth at the Solling control plot B1 (**a**), soil nitrate concentrations at 10 cm depth (**b**) and N_2O emissions (**c**) at the beech site at Solling (*B1*), a fertilized plot (*BN*), and a limed plot (*BK*) at the Solling site for January 1993 to March 1995

after fertilization when compared to soils under forests, and also to more microsites with low oxygen diffusivity (compacted soil) under agricultural conditions.

Liming of acid forest soils is very common in Germany (Meiwes 1994; AFZ 1995) and has been found to reduce the N_2O emissions by 74% after 5 years of applying 30 tons of dolomitic limestone at the BK plot when compared to the control B1 plot at the Solling site (Brumme and Beese 1992). In the 11th and 12th years after liming, the N_2O emissions were still low (83% or 0.41 kg N ha^{-1} per year) (Table 18.1, Fig. 18.8). A reduction of N_2O emissions by liming was also observed in a forest gap at the Solling site where 3 tons of dolomite ha^{-1} was worked into the upper soil after harvesting (Fig. 18.7). In contrast to the unlimed gap where a ground vegetation cover of <5% occurred, the limed gap showed about 90% of the area covered with ground vegetation after 2 years of clear-cut (Bartsch et al. 2002). Dense ground vegetation would lead to a decrease in soil moisture, nitrate, and N_2O emissions during the growing season. Moreover, a high population of earthworms in the mineral soil (Theenhaus and Schaefer 1995) might have contributed to the reduction in N_2O emissions by increasing macropores. Borken and Brumme (1997) reported that 9–82% reduction of N_2O emissions in separate field experiments occurred where lime was applied 5–19 years ago to beech and spruce forests. At the Höglwald site, the effect of a higher diffusivity (Schack-Kirchner and Hildebrand 1998) after the establishment of earthworms in the surface organic layer after liming (Ammer and Makeschin 1994) increased the N_2O emission (Papen and Butterbach-Bahl 1999). In this study, the effect of a higher diffusivity may have been overcompensated by an increase in net nitrification rates.

Soil compaction during harvesting caused a considerable increase in N_2O emissions, with values elevated by up to 40 times of those on the uncompacted soil (Teepe et al. 2004). These changes were caused by a reduction in macropore volume and an increase of the water-filled pore space. N_2O emissions were altered in the trafficked soil and in the adjacent areas. Despite the significant changes in N_2O emission, the cumulative effect on the atmosphere was small with respect to the soil trafficking. The fractional area on the skid trails to total area as calculated by Teepe et al. (2004) was 13%, considering a distance of 20 m between skid trails which is commonly used in Germany. The cumulative values of increase due to compaction were approximately 0.1 kg N_2O–N ha^{-1} per year for the sandy loam and silty clay loam sites and 0.3 kg N_2O–N ha^{-1} per year for the silt site.

18.8 Conclusions

- The N_2O emissions from the acid soil at Solling (B1 plot) was up to 15 times higher than from the less acid soils at Zierenberg (0.41 kg N ha^{-1} per year) and Göttinger Wald (0.16 kg N ha^{-1} per year). The high values of N_2O emissions at the Solling site were mainly related to a strong seasonal pattern of N_2O emissions at that site. These high N_2O emission values at the Solling site were attributed to reduced oxygen diffusion in the surface organic layer (densely packed leaves acted as a diffusion barrier) and in the mineral soil (high bulk density).
- Soil temperature was the main factor determining N_2O emissions at the Solling site except for the periods when soils were dry (soil water tensions >200 hPa) in summer and autumn months. High temperatures caused a seasonal pattern of N_2O emissions, as compared to the commonly observed background patterns.
- Forests with seasonal N_2O emissions (as at the Solling site) responded much more strongly to temperature increase (apparent Q_{10} = 9) than forests with background N_2O emissions such as the Göttinger Wald or Zierenberg sites. The strong response to temperature increase was explained by higher oxygen consumption and increased anaerobic zones in the soil. Forests with a seasonal

emission pattern may therefore increase the global N_2O budget if the temperature increases.

- High spatial variations of N_2O emissions were partly related to the heterogeneous distribution of fine root biomass on the Solling site. High numbers of replicates are required to assess mean N_2O emissions from a forest site.
- Forest clearing may affect N_2O production in forests by restricting oxygen diffusion as it was observed in the moder-like humus soil at the Solling site. High soil moisture and nitrate content in a forest gap increased the period of high N_2O emissions in summer and autumn months and led to 3–5 times higher annual fluxes. Forest harvesting did not affect N_2O emissions at the Zierenberg site. This may be related to the well aerated soil and the low background N_2O emissions at this site, and to the fast development of a dense ground vegetation, reducing nitrate and water content in the soil.
- Liming reduced the N_2O emissions by improving oxygen diffusion in soils through an increase in the faunal activity that improved bioturbation in soils (removing the diffusion barrier in the surface organic layer). Liming increased ground vegetation cover and further reduced N_2O emissions by lowering moisture content in the soil. The recent liming to forests may have long-term effects on the N_2O emissions as is indicated by low values in up to 19-year-old liming plots.
- In order to reduce the N_2O emissions from beech forests, it is important to reduce the seasonal N_2O emissions through adequate soil aeration which may be achieved in many situations by liming and by keeping soil compaction low during forest operations.

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