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Nitrous oxide emission from a range of land uses across Europe

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Abstract

The results of a literature study examining quantitative estimates of N_2O emission rates are presented for a range of land-uses across Europe. The analysis shows that the highest N_2O emission rates are for agricultural lands compared to forests and grasslands. The main factors regulating these rates are available mineral nitrogen, soil temperature, soil water content and the available labile organic compounds. These controls operate across different time-scales, all must exceed a certain threshold for N_2O emission to occur. The results support the need for an emission factor function of land-use and climate within models describing nitrogen dynamics in catchments. This would allow the assessment of the net N_2O emission within catchments in terms of current levels and potential changes associated with climate variability, climate change and land use change.

Keywords: nitrous oxide, soil water content, inorganic N, soil temperature, ecosystems, land-use management, soil type

Introduction

Soils are the most important source of atmospheric nitrous oxide (N_2O), contributing an estimated 70% to the total globally emitted N_2O (Bouwman, 1990). To the extent that soils are managed, especially if they receive nitrogen fertilisers, or are impacted upon by atmospheric N deposition, they are also an anthropogenic source of N_2O. Other sources of N_2O are the oceans, biomass burning and emissions from industrial processes and automobiles (Bange, 2000). Nitrous oxide is of great interest from an environmental point of view because it is an important greenhouse gas present in the lower atmosphere (the troposphere) at about 0.00003%. Although N_2O constitutes only 6% of the anthropogenic greenhouse effect (Bouwman, 1998), it has a radiative forcing 180 times greater than carbon dioxide (Lashof and Ahuja, 1990; Mogge *et al*., 1998). It also contributes to the depletion of stratospheric ozone. Over the last 25 years the concentration of N_2O in the atmosphere has risen by about 0.25% per year (Flessa *et al*., 1995). In comparison, the atmospheric concentration of carbon dioxide has been increasing at about 0.3% per year since the 1960s and that of methane, another greenhouse gas, by 1% per year.

N_2O is both emitted and absorbed by soils, but the net flux is almost always emission. Due to seasonal and spatial variation, N_2O emissions are difficult to quantify (Smith *et al*., 1994) and the estimation of annual emissions from a small number of observations may lead to considerable errors. This emphasises the need for long-term studies to overcome the problem.

A recent review by Wrage *et al.* (2001) brought together information on N_2O fluxes, but only for nitrifier denitrification. This paper provides a more comprehensive review of N_2O fluxes for a range of land-uses across Europe from all sources. This work aims to identify the main factors influencing these emissions and to compare N_2O emission estimates for different ecosystems (forests, grasslands and agricultural land).

Processes

Two mechanisms are mainly responsible for N_2O emissions from soils: microbial nitrification and denitrification (Table 1). A third, not well known process has recently been studied by Wrage *et al.* (2001): nitrifier denitrification. This process

Table 1. Factors favouring Nitrification and Denitrification processes

	Nitrification	*Denitrification*
Substrate availability	NH_4^+, urea, amino acids	NO_3^-
O_2 concentration	high	low
reduced carbon	No effect	high (energy source)
moisture (water filled pore space)	intermediate 30-70 % WFPS	high 55-100 % WFPS
soil temperature	high (within range)	high (within range)
pH	> 5	Low (< 5)

is carried out by autotrophic nitrifiers that oxidize ammonia (NH_3) to nitrite (NO_2^-) and then reduce NO_2^- to nitric oxide (NO), nitrous oxide (N_2O) and molecular nitrogen (N_2). Nitrifier denitrification can lead to substantial N_2O emissions especially when low oxygen conditions are coupled with low organic carbon contents of soils and low pH. The maximum amount of N_2O lost via nitrifier denitrification in soils represents about 30% of the total N_2O production (Webster and Hopkins, 1996).

Nitrification consists of the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and then nitrate (NO_3^-). It is an aerobic process carried out by a few genera of autotrophic bacteria able to use the energy generated from these processes. The best studied are the obligate chemoautotrophs, *Nitrosomonas* and *Nitrobacter* species (Robertson and Kuenen, 1991). At sub-optimal oxygen concentrations oxidation into NO_3^- is incomplete and some of the NH_4^+ is channelled into the production of NO and N_2O (Poth and Focht, 1985). Bremner and Blackmer (1981) report that N_2O production is higher with added nitrifiable nitrogen (e.g. urea or ammonium containing fertiliser). Nitrification occurs most rapidly when soil pH is between 5.5 and 6.5 (Kasica, 1997). For instance, nitrification rates from pasture soils have been found to be higher in the zone of the soil with a pH value of 5.7 than in a deeper soil layer with a pH value of 4.7 (Black *et al*., 1998). In the field, nitrification can also be controlled by the moisture content and temperature of the soil.

Denitrification is the anaerobic process by which nitrate (NO_3^-) and nitrite (NO_2^-) are reduced to give nitric oxide (NO), nitrous oxide (N_2O) and dinitrogen (N_2). It requires a ready supply of reduced carbon for energy and NO_3^- as a substrate. A wide range of micro-organisms can denitrify. They are facultative anaerobes and switch to NO_3^- as a terminal electron acceptor when oxygen is unavailable. Important environmental controls for denitrification include temperature, soil moisture and pH. Denitrification will have different products depending on the level of soil moisture, with NO favoured by lower soil moisture grading into N_2 favoured at the highest soil moisture. However, it is still unclear exactly what level of soil moisture will lead to primarily NO, N_2O or N_2.

The extent to which these two processes, nitrification and denitrification, contribute to N_2O emission will vary with climate, soil conditions and soil management. Generally, high rainfall, poor drainage, fine soil texture and high organic carbon content promote denitrification whereas low rainfall, good drainage and aeration and coarse texture promote nitrification (Groffman, 1991). However, due to the complex interactions of the factors influencing the processes, it is difficult in most soils to determine which process prevails and what proportion of the nitrogen released is N_2O. The processes of denitrification and nitrification can also co-occur at the same time in a single site due to micro-scale soil heterogeneity and the balance between the two processes can switch very rapidly.

Material description and methods

The analysis was made by compiling data from reviews and site-specific field experiments on N_2O flux controls for a variety of European ecosystems (Appendix 1). The 33 individual experiments from 13 references are from grasslands (fertilised or non-fertilised), forests (subjected to variable amounts of atmospheric N deposition) and agricultural sites (different crop types) across Europe. Only studies with at least 1 year's data are included. The determination of N_2O emission rates for all of the 13 references considered was made using the closed chamber method (Hutchinson and Mosier, 1981) and gas samples were then analysed by gas chromatography. The standard soil- and weather-dependent parameters were measured in most cases. These include monitoring of precipitation, air temperatures, soil temperatures at different depths (digital thermometer), water-table levels and pH of soil in water. Soil water content was determined and results were given either as volumetric water content, gravimetric water content (wt/wt) or as water filled pore space. Soil analysis for nitrate and ammonium concentrations (KCl or $KAl(SO_4)_2$, Papen

and Butterbach-Bahl, 1999, extractions) were also performed. The water-soluble organic carbon compounds were determined in the method described in Burford and Bremner (1975) and the soil organic matter as Loss-On Ignition method.

Results

Brumme *et al.* (1999) report a study of eleven forest ecosystems in Germany comprising mainly alder, beech and spruce (Table 2). Element budgets and soil characteristics were measured in these forests and showed distinct differences between sites, including pH ranging from 3.6 to 5.6. Nitrogen deposition ranged from 20 to 41 kg N ha^{-1} yr^{-1}. In these ecosystems, the soil surfaces were more or less covered by herbaceous vegetation. Nitrous oxide emissions were measured weekly or biweekly over one year with closed chambers.

Brumme *et al.* (1999) distinguished three types of emission patterns determined by the differences in temporal variation: (a) 'seasonal' emission pattern, (b) 'event-based' emission pattern and (c) 'background' emission pattern. The 'background' pattern is characterised by low annual fluxes. They found that most sites show background emission patterns, with low emissions during the whole year and low annual site means ranging from 0.17 to 0.80 kg N_2O-N ha^{-1} yr^{-1} (Table 2). Similar and relatively constant N_2O emissions were found in one forest in Finland (Martikainen *et al.,* 1994), three forests in the UK (Skiba *et al.,* 1996), one other forest in Germany (Mogge *et al.,* 1998) and two forests in Denmark (Ambus and Christensen, 1995), with annual emissions ranging from 0.12 to 0.8 kg N_2O-N ha^{-1} yr^{-1} (Appendix 1). Only two of the sites studied by Brumme *et al.* (1999) appeared to display 'seasonal' patterns. Such sites are characterised by a period of elevated rates in summer. These two sites had much higher annual fluxes: 3.0 and 7.3 kg N_2O-N ha^{-1} yr^{-1} (Table 2). Some of the forested sites listed in Appendix 1 show similar fluxes. The 'event' emission pattern is characterised by short peaks of N_2O emission during or following periods such as frost or thaw. Brumme *et al.* (1999) observed this type of emission at a drained site in Germany, with N_2O flux changing from 100 µg N_2O-N m^{-2} h^{-1} to about 500 µg N_2O-N m^{-2} h^{-1} with the onset of the spring thaw in 1996.

The results from the 33 sites together with the data from Brumme *et al.* (1999) are presented in Fig. 1. These data indicate a gradient of N_2O emissions with low fluxes for forests and grasslands, and higher emissions from agricultural fields. However, five forested sites show N_2O emissions within the same range obtained for the arable agricultural sites; these are in Höglwald (two sites), Solling, Schelswig-Holstein and Bornhöved in Germany. Annual emissions were 2.18 kg N_2O-N ha^{-1} yr^{-1}, 3 kg N_2O-N ha^{-1} yr^{-1}, 3.81 kg N_2O-N ha^{-1} yr^{-1}, 4.9 kg N_2O-N ha^{-1} yr^{-1} and 7.3

Table 2. Annual losses of nitrous oxide and some site characteristics

Site location	*Vegetation*	*N_2O kg N_2O-N ha^{-1} yr^{-1}*	*Soil Bulk density (0-5 cm) g cm^{-3}*	*Precipitation mm yr^{-1}*	*N^c deposition Kg N $ha^{-1}yr^{-1}$*	*Type of flux*
Bornhoved (d)	alder	7.3	0.48	697	33	s
Solling	beech	3.0	1.01	1090	35	s
Harz	spruce	1.3	1.2	1239	20	b
Bornhoved	alder	0.80	-	697	33	e
Lappwald	spruce	0.56	1.2	650	-	b
Zierenberg	beech	0.41	0.75	700	21	b
Harste	beech	0.36	1.17	750	26	b
Lappwald	beech/oak	0.29	0.85	650	-	b
Solling	spruce	0.26	0.91	1090	41	b
Spanbeck	spruce	0.21	1.01	650	31	b
Gottinger Wald	beech	0.17	0.79	680	28	b

Data from Brumme *et al.* (1999)
(d) – drained
[c] Throughfall of $NH_4^+ + NO_3^- + N_{org}$
s = 'seasonal'; b = 'background'; e = 'event-based'

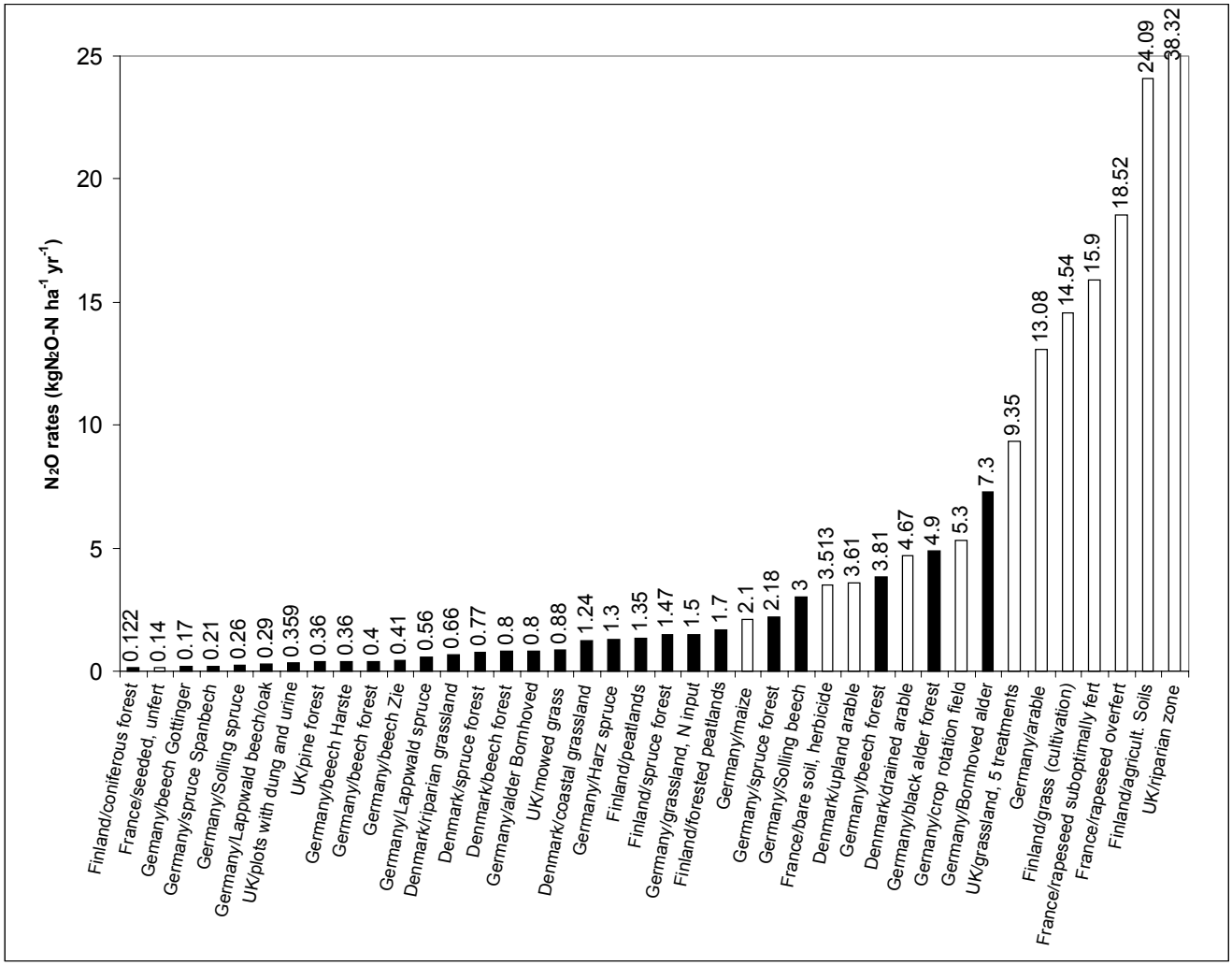

Fig. 1 *Nitrous oxide emission rates for different European ecosystems - Black bars represent the forested and grassland ecosystems. White bars represent the agricultural ecosystems*

kg N_2O-N ha^{-1} yr^{-1} respectively. Germany is among the European countries receiving the highest atmospheric N deposition as oxidised or reduced nitrogen. The mean annual precipitation for these regions is about 850 mm. The soils are acidic and mostly organic.

Discussion

Nitrous oxide emissions from soils have been widely studied in the past decades and it is generally agreed that the main processes responsible for emissions, namely nitrification and denitrification, are not controlled by only one parameter but by several interacting parameters making predictions very difficult.

SOIL MOISTURE, BULK DENSITY, RAINFALL

Hydrological factors seem to exert the strongest controls on annual N_2O emissions for most of the sites studied by Brumme *et al.*(1999). These factors affect nitrification and denitrification in different ways. Denitrification will be favoured by high moisture contents whereas nitrification will occur in drier soils. For instance, it has been observed (Davidson, 1991) that nitrification is the dominant source of N_2O when water filled pore space (WFPS, calculated using gravimetric water content) is less than 60% and that denitrification is the predominant source when WFPS is greater than 60%. By comparison, Fig. 2 shows the relationship between annual N_2O emissions and bulk density (data from Brumme *et al.,* 1999). There is no strong correlation. In addition, the data obtained by Brumme *et al.*

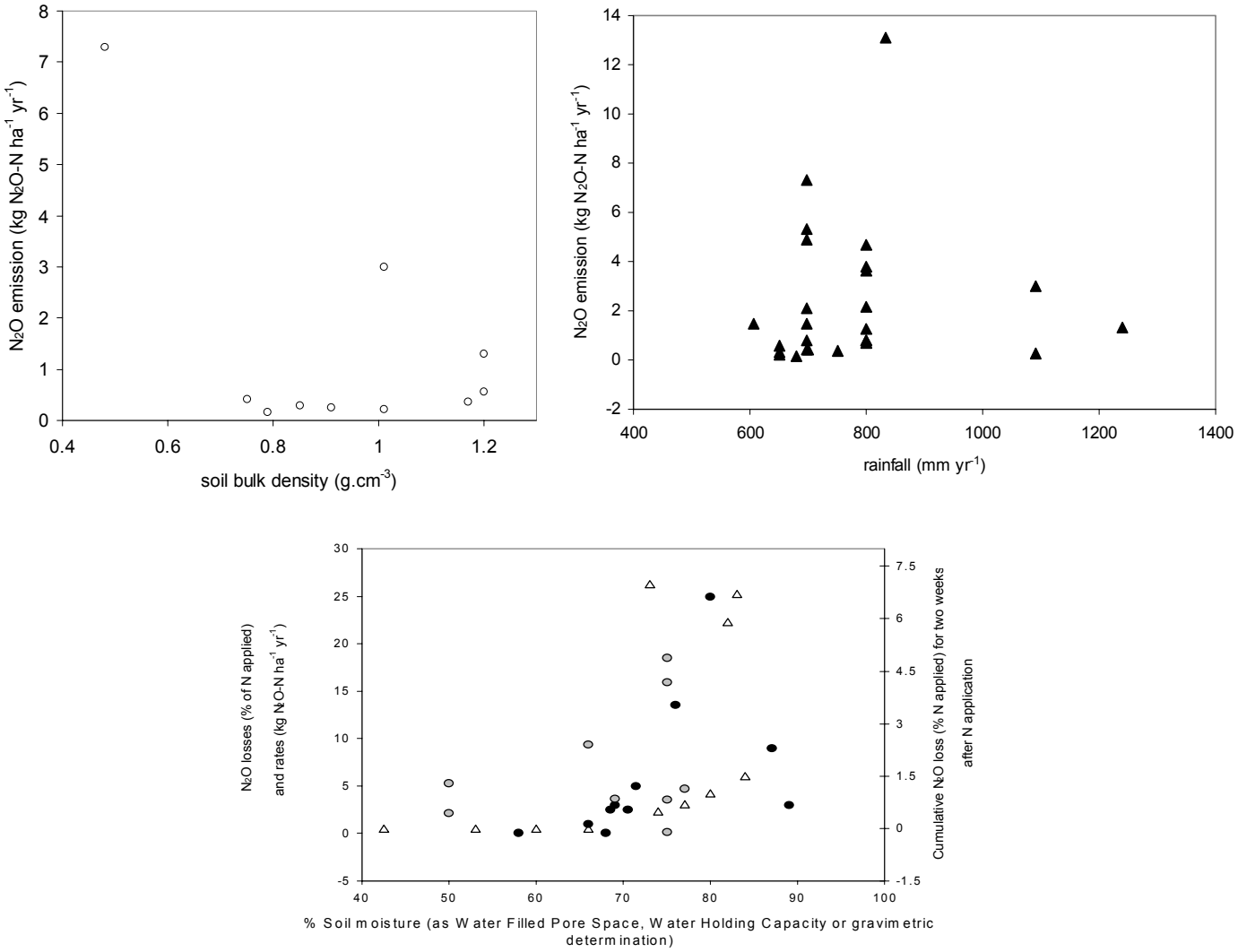

Fig. 2. *Relationships between annual nitrous oxide emissions and soil bulk density, annual precipitation and soil moisture. (▲) All data (13 references from Appendix 1 and Brumme* et al.*, 1999). (❍) Data points from Brumme* et al., *1999. (●) Data set for sugar cane, banana and pasture in the tropics of Costa Rica. The data were redrawn from Veldkamp* et al. *(1998). (Δ) Data points from managed grassland in W. Europe (Dobbie* et al.*, 1999). Grey circles represent the data from agricultural soils in Europe (see studies in Appendix 1). The scale for the N_2O data from the tropical soils and from the agricultural data is on the left side of the graph, from the grassland data on the right side of the graph.*

(1999) and those from the 13 references considered in Appendix 1 show that no strong relationship exists between N_2O emissions and rainfall (Fig. 2).

High N_2O emissions measured by Brumme *et al.* (1999) took place when the soil water content was near field capacity (~1kPa) and lasted until the soil water suction reached 2kPa. Once this threshold was reached, N_2O emissions decreased. In the study of Skiba *et al.* (1996) daily and even seasonal changes in moisture were not very well correlated with N_2O fluxes. However, they observed a strong correlation between annual precipitation and annual N_2O fluxes. Their data for a coniferous forest in central Scotland gives some clues about the relative importance of temperature and soil moisture. They observed, for the same soil, that wetter soil at lower temperatures had higher fluxes than drier soil at higher temperatures (0.47 kg N ha^{-1} with a mean soil moisture content of 34% of soil dry weight and average soil temperature of 10ºC for 1993; and 0.3 kg N ha^{-1} with a mean soil moisture content of 25% of soil dry weight and average soil temperature of 12ºC for 1994). Mogge *et al.* (1998), in their study of two forest sites in Höglwald, Germany, show that an increase in soil moisture, due to precipitation, contributed to the high N_2O emissions observed at both sites (precipitation recorded from July to September and in December). The same positive correlation was reported in another of their studies (Mogge *et al.,* 1999). The literature also suggests that a threshold for soil gravimetric water content of about 60–70% exists above

which significant N_2O emission can be obtained. In temperate climates (Dobbie *et al.,* 1999) as well as in the tropics (Veldkamp *et al.,* 1998), maximum N_2O emissions have been found to occur at a water filled pore space (WFPS) of 75–85% (weight/weight, Fig.2). This has also been found across Europe for different ecosystems (Mogge *et al*., 1998; Ruser *et al*., 1998). As well as regulating the emission rate, water filled pore space regulates the proportion of N_2O emission from nitrification and denitrification due to its effect on O_2 diffusion. In soils with good oxygen supply, emission of NO should dominate while N_2O may be the main product in moderately aerated soils. Nitrous oxide and NO losses are both high in poorly aerated soils and only in very poorly aerated soils (waterlogged soils with Eh close to 0V) does N_2 emission dominate.

Soil moisture is clearly influencing N_2O emissions whereas rainfall shows no clear relationship with fluxes. This may be a result of the different response soils have to rainfall according to their nature. For instance, where soils contain higher percentages of clay, diffusion of the water through the soil will be slower and high rainfall will not necessarily result in higher soil moisture content. Also, part of the rainfall will be accounted for as runoff water.

N INPUT, N OUTPUT, N FERTILISATION, N SATURATION

Nitrogen availability is another control for nitrification and denitrification, but different forms of inorganic N will have different effects: NH_4^+ availability will influence nitrification, and denitrification will be affected by NO_3^- availability (Table 1). However, the two processes are closely linked, since NO_3^- ions are produced by nitrification of NH_4^+. It is still unclear what the minimum concentrations for NO_3^- and NH_4^+ are below which denitrification or nitrification will not occur.

Data on forested ecosystems in Europe (NITREX, Matzner, 1989) showed that nitrogen deposition affects the excess of nitrogen in the soil solution. Brumme *et al.* (1999) did not find any effect of N deposition on N_2O emissions from sites with background emissions, presumably where N deposition did not result in excess mineral N in the soil. However, they observed high N_2O emissions from the two sites where 'seasonal' emissions were observed. It is unclear why such high emissions were found at the Solling beech stand and in the case of the drained alder forest in Bornhöved it could be explained by the fact that alders are N-fixing species which can exude nitrate into the soil from their nodules and also produce leaf litter with a high N content. The Intergovernmental Panel on Climate Change (1997) estimated that 1% of the N supplied by atmospheric deposition to natural soils is emitted as N_2O. This is a simple estimate (or 'default value') based on readily available input data. In Fig. 3, the data points significantly above the 1% IPCC default line are from sites which had received continuous elevated N deposition rates for many years. Many of the values below this line but receiving high N deposition are from field experiments where elevated N deposition was simulated for a relatively short time. In the sites studied by Brumme *et al.* (1999), the minimum N deposition is about 20 kg N $ha^{-1}yr^{-1}$ (Table 2). Applying fertiliser only seemed to generate pulses of N_2O emission but showed no long-term effect. Results for agricultural sites from Skiba *et al.* (1996) showed a positive response of N_2O emissions a few weeks after fertilisation. This has also been observed by Mogge *et al.* (1999). Moreover, the timing of fertiliser application appears to be an important factor affecting annual fluxes, with higher annual N_2O fluxes if fertiliser is applied during warmer months. Major increases in N_2O flux can occur shortly after fertilisation, with near background emissions restored within several weeks after application (Skiba and Smith, 2000).

Together, the N-deposition and N-fertilisation data suggest that the 'N status' of the sites, i.e. the availability of mineral N substrate for nitrification and denitrification (applied, or derived from organic N applied), is probably a secondary control for N_2O emissions after moisture and temperature. However, N_2O emission will only occur if a minimum level of N substrate is present in the sites. It may also be that N_2O losses will increase linearly with N input once the system has reached optimum levels of the other factors controlling N_2O emission.

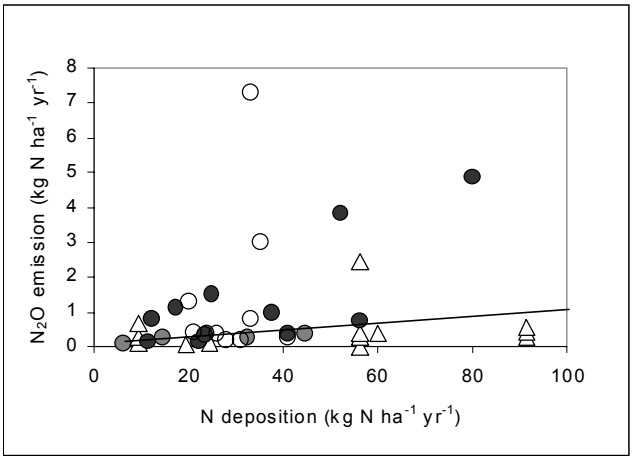

Fig. 3. *N deposition induced emissions from forest and moorland soils. In upland areas (grey circles), large-scale acid mist experiments (Δ), downwind of point sources: poultry and pig farms (●), and German forests (○), IPCC emission factor 1% (solid line).*

CARBON SOURCE, LITTER QUALITY, CROP TYPE

Another factor to be considered when looking at N_2O emissions is the carbon source. This is an important control for denitrification. In their study, Brumme *et al.* (1999) looked at the effect on annual N_2O emissions of the mass of the organic horizon in the soils studied (Fig. 4). Unfortunately there are not enough data to draw definite conclusions. Figure 4 suggests that an increase in the mass of the upper organic horizon provides an additional carbon source for nitrification/denitrification for which it might be possible to determine a threshold with more data. Nitrous oxide fluxes may be higher for organic upper horizon >100 t ha^{-1}. However, as for nitrogen inputs, this only seems to have a secondary effect on N_2O emissions.

Different crop types appear to emit different amounts of N_2O. This has been shown by Skiba *et al.* (1996) in their study of a range of agricultural and semi-natural soils in south and central Scotland. For instance, a potato crop emitted more N_2O than cereals. An explanation for this was the contribution of more labile crop residues following harvest, and root exudation during tuber development. Dobbie *et al.* (1999) obtained higher emission factors from potato and brassica crops (1.8–7% of N applied) than for wheat and barley (0.2–0.7% of N applied). This was also found by Henault *et al.* (1998) for wheat compared to oil seed rape (0.42 compared to 0.55%). Similar observations have been made by Brumme *et al.* (1999) regarding the litter quality in forested ecosystems. In an experiment where litter fall between beech and spruce stands was exchanged (Solling, Germany), N_2O emissions increased in the spruce stand after application of beech litter and decreased in the beech stand after spruce litter had been applied. However, the change in N_2O flux between controls and treated plots was much less than the actual differences between control stands, suggesting either that a longer time is needed to obtain a flux response or that other factors are important.

TEMPERATURE

Both nitrification and denitrification rates are controlled by soil temperature. The rapid increase in process rates with increasing temperature suggests that the response to temperature is primarily a biochemical response rather than a population one. Temperature is also a daily control and a fast response parameter. Seasonal and diurnal changes in temperature have been shown to be correlated, directly and linearly, with N_2O emission for many soils in temperate climates (Skiba *et al.,* 1998; Skiba and Smith*,* 2000). But this is only true when other important factors such as WFPS or mineral N are not limiting. This was shown by Dobbie *et al.* (1999) in their study of intensively managed agricultural fields, with Q_{10} values of up to 8. In their study of 11 forest soils in Germany, Brumme *et al.* (1999) observed an increase of the N_2O emission from 6 µg N_2O-N m^{-2} h^{-1} up to a more or less constant level of about 90 µg N_2O-N m^{-2} h^{-1} when soil temperature exceeded 10°C. Their data also indicated that during the period of high emissions N_2O fluxes followed changes in temperature. The Q_{10} values obtained for this same study were as high as 14. Such an extremely high Q_{10} is partially explained by temperature-induced positive feedback. For instance, a rise in temperature will have an effect on soil respiration and anaerobicity thus influencing nitrification and denitrification rates (Smith, 1997). In addition, the data obtained by Brumme *et al.* (1999) show that N_2O fluxes are related to the air temperature (Fig. 5) with small fluxes at temperatures below 8°C and larger fluxes more likely to happen at higher temperature, but depending on other factors. N_2O fluxes will also be related

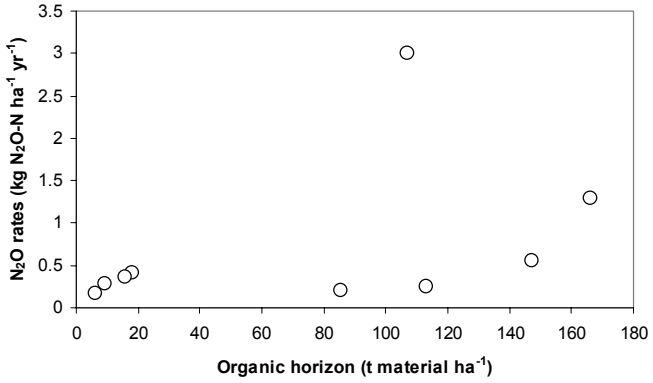

Fig. 4. *Relationship between annual nitrous oxide rates and the total mass of material in the organic upper horizon. Data from Brumme* et al., *1999*

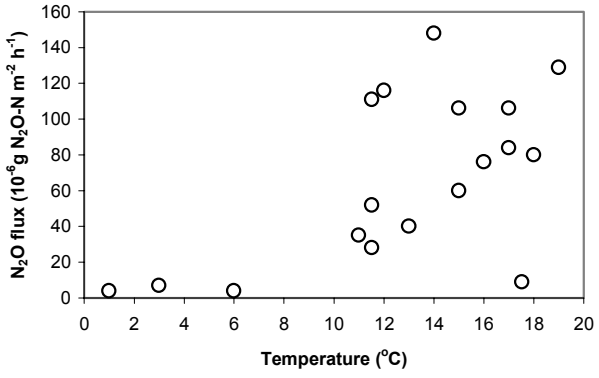

Fig. 5. *Relationship between annual air temperature and N_2O flux. Data redrawn from Brumme* et al.,*1999.*

to the soil temperature since the soil temperature is related to air temperature but is lagged with time and damped with depth. For the Brumme *et al.* (1999) study, only air temperature was available. This is often the case since air temperature are readily available.

Studies such as Mogge *et al.* (1999), Flessa *et al.* (1995) or Papen and Butterbach-Bahl (1999) showed peaks of N_2O emissions during freeze-thaw periods. Brumme *et al.* (1999) also showed that freeze-thaw influences N_2O fluxes but only at one of the sites studied. The effect of temperature on N_2O emission can be counteracted by its stimulating effect on plant growth, thus enhancing the competition for NO_3^- and NH_4^+.

More generally, denitrifying organisms can adapt to local temperatures (and possibly other local conditions): Powlson *et al.* (1988) showed that denitrifiers from England and Australia denitrified at the same rate when at local optimum temperatures of 10 and 20ºC, respectively.

NET EFFECT

The response of N_2O emissions to factors such as soil moisture, rainfall, N deposition, N fertilisation, carbon source, crop type or temperature is very variable and depends on the interactions of these factors with each other. A better way to estimate and predict N_2O emissions in different European ecosystems might be to use emission functions developed from empirical models that use broad controlling factors such as land use and climate. Figure 1 shows a clear difference between land uses such as forests or agriculture. An interactive multilayered model in which the controls would be activated by thresholds is shown in Fig. 6. These operate over different time scales. For instance, hydrology and mean annual soil temperature are long-term site attributes that are regulated by the regional climate, topography, etc. These establish the overall potential of the site for N_2O fluxes.

Threshold values of dissolved inorganic N and DOC and WFPS are then required for actual denitrification or nitrification. Variation in these over a seasonal to weekly time scale will affect the amount of N_2O released over a given season. Changes in these values may not immediately affect N_2O fluxes since they may operate by changing competitive relationships among different populations of micro-organisms. Shifts in these relationships may take place after a time lag. A change in soil temperature, however, may immediately affect N_2O fluxes as it operates on the biochemical scale. If any of the controlling factors is below the threshold, N_2O flux will not occur. This concept is similar to that developed by Skiba and Smith (2000) for agricultural systems, and by Ulrich (1994) and Brumme *et al.* (1999) for forest ecosystems.

Conclusion

Nitrous oxide emissions vary widely. Results from European studies show that N_2O emissions are not strongly correlated to precipitation whereas soil moisture levels are a major control, interacting with secondary controls such as N deposition, fertiliser use, carbon source and soil temperature. Nitrous oxide emissions will occur when these controlling factors are not limiting, i.e. above a certain threshold. Furthermore, the complexity of these interactions makes prediction of N_2O emissions and simple relationships between fluxes and factors difficult to obtain. In order to derive more reliable estimates of N_2O emission, interactive

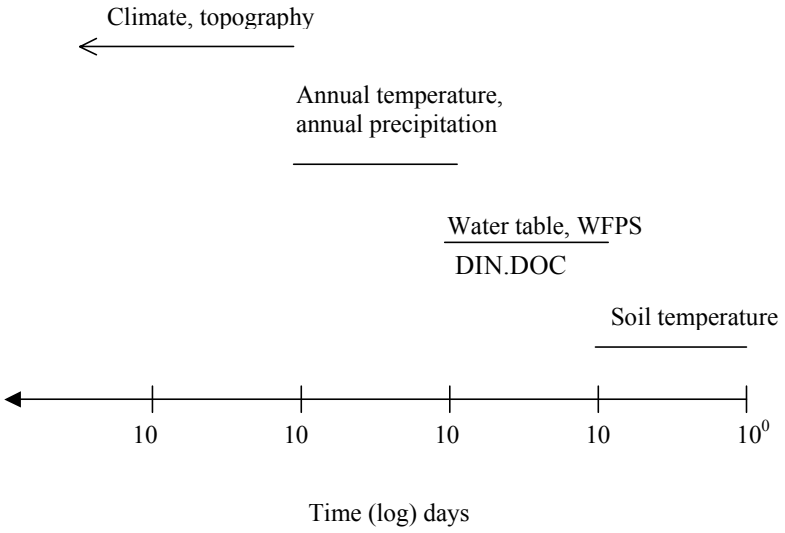

Fig. 6. *Major controls on denitrification and nitrification, and approximate time scale of change of importance to N_2O fluxes*

multilayered models are needed which describe N dynamics and N_2O emissions as function of climate and land use. While these models are lacking, the use of emission factors such as those proposed by the IPCC (1997) or Brown *et al.* (2001) offer the simplest way to estimate N_2O emissions. However, as Brown *et al.* (2001) show, the IPCC default values are gross approximations. Those wanting more precise estimates must resort to site-specific measurements or dynamic models such as DNDC (Li *et al.,* 1992, 1996) or SUNDIAL (Smith *et al.,* 1996).

Acknowledgements

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Appendix 1. Nitrous oxide emission rates in Europe, ecosystem types and soil characteristics

Country	*Ecosystem type* *Measurement period*	*Soil type*	*Annual N_2O rate* *(kgN_2O-N* ha^{-1} yr^{-1})	*monitored parameters*	*pH*	*soil temp*	*moisture %* *g soil*	*Corg* *Mg C/*	*N inputs* *kgN/ha*	*rainfall* *mm yr^{-1}*	*literature reference*
Denmark 3 yrs (1990-1992)	Riparian grassland	well to poorly drained organic soils	0.66	moisture, inorganic N, SOM, pH	8	8.3	57	303 (vol.)	-	800	Ambus and Christensen, 1995
Spruce forest	well drained loamy sand 3 yrs (1990-1992)	0.77	moisture, inorganic N, SOM, pH		4	8.45	60	369 (vol.)	-	800	Ambus and Christensen, 1995
	Beech forest 3 yrs (1990-1992)	well drained sandy loam	0.8	moisture, inorganic N, SOM, pH	5.6	7.9	54	36.3 (vol.)	-	800	Ambus and Christensen, 1995
	Coastal grassland 3 yrs (1990-1992)	well to poorly drained sandy soil	1.24	moisture, inorganic N, SOM, pH	7	7.25	86	120 (vol.)	-	800	Ambus and Christensen, 1995
	Upland arable fertilised 3 yrs (1990-1992)	somewhat to poorly drained sandy loam	3.61	soil moisture, inorganic N, pH, SOM	7.6	9.75	69	164 (vol.)	180	800	Ambus and Christensen, 1995
	Drained arable fertilised 3 yrs (1990-1992)	poorly drained loam	4.67	soil moisture, inorganic N, pH, SOM	7.7	10.95	77	164	110	800	Ambus and Christensen, 1995
	Peatlands (1991-1992)	peat soils organic	1.35	total N, pH, water table, P, K, Ca contents	4.4	8.5	-	-	-	-	Regina *et al.*, 1996
	Spruce forest clearcutting, drainage area (1993-1994)	peat soils underlain by sandy till/clay organic	1.47	total N, inorganic N, soil temperature	acid	7	-	-	6.25	607	Nieminen, 1998
	Forested peatlands (1991-1992)	peat soil organic	1.7	total N, pH, water table, P, K, Ca contents	4.4	8.5	-	-	-	-	Regina *et al.*, 1996
	Grass (cultivation), high N Content (1991-1992)	peat soil organic	14.54	total N, pH, water table, P, K,Ca contents	5.3	8.5	-	-	-	-	Regina *et al.*, 1996
	Agricultural, low N Deposition (1991-1992)	mineral soils organic	0.929 23.23	pH, soil temperature	acid	8.5	-	-	-	-	Martikainen *et al.*, 1994
France	Agricultural (seeded, unfertilised) 12 months (1994-1995)	3 soils*	0.14	moisture, soil temperature and soil nitrate	7.3	10.5	75 (WFPS)	18.7	-	-	Henault *et al.*, 1998
	Agricultural (bare soil, herbicide) 12 months (1994-1995)	3 soils*	3.513	moisture, soil temperature and soil nitrate	7.3	10.5	75 (WFPS)	18.7	-	-	Henault *et al.*, 1998

Apppendix 1 (contd.)

	Agricultural (rapeseed, suboptimally fertilised) 12 months (1994-1995)	3 soils*	15.9	moisture, soil temperature and soil nitrate	7.3	10.5	75 (WFPS)	18.7	153	-	Henault *et al.*, 1998
	Agricultural (rapeseed, overfertilised) 12 months (1994-1995)	3 soils*	18.52	moisture, soil temperature and soil nitrate	7.3	10.5	75 (WFPS)	18.7	257	-	Henault *et al.*, 1998
Germany	Beech forest 12 months (1993)	loamy sand sedimentary origine	0.4	moisture, soil temperature, nitrate, water soluble organic C	4	9	50 (wt/wt)	34	23.8	697	Mogge *et al.*, 1998
	Grassland, N input 12 months (1993)	sedimentary origine, loamy sand	1.5	soil moisture, nitrate, pH, soil temperature, water soluble organic C	6.4	11.5	30 (wt/wt)	16.5	78	697	Mogge *et al.*, 1999
	Maize monoculture, Cattle slurry fertilised 12 months (1993)	sandy soil	2.1	soil moisture, nitrate, pH, temperature, water soluble org. C	5.4	11.5	50 (wt/wt)	12.1	319	697	Mogge *et al.*, 1999
	Spruce forest 3 yrs (1994-1996)	very acid hapludalf	2.18	soil ammonium and nitrate, soil moisture and temperature	3.5	6.65	33.5 (WFPS)	-	30	800	Papen and Butterbach-Bahl, 1999
	Beech forest 3 yrs (1994-1996)	very acid hapludalf	3.81	soil ammonium and nitrate, soil moisture and temperature	4	6.65	33.5 (WFPS)	-	20	800	Papen and Butterbach-Bahl, 1999
	Black Alder forest 12 months (1993)	forest soil on peat	4.9	pH, moisture, soil temperature, nitrate, water soluble organic C	4	9	70 (wt/wt)	422	69	829	Mogge *et al.*, 1998
	Agricultural (crop rotation field), farmyard manure fertilised 12 months (1993)	loamy sand	5.3	soil water, nitrate, temperature, water soluble organic C	6.4	11.5	50 (wt/wt)	12.8	79	697	Mogge *et al.*, 1999
	Arable, fertilised (FYM, CaNH4NO3) 12 months (1993)	sandy and clay soils	13.08 moisture	soil temperature,nitrate,	6.1	-	-	16.9	124	833	Flessa *et al.*, 1995
UK	Sitka Spruce forest 3 yrs (1992-1994)	brown forest soil	0.35	pH, moisture, soil nitrate and ammonium, soil temperature	3.9	10	29 (wt/wt)	-	58	800	Skiba *et al.*, 1996

Apppendix 1 (contd.)

Long term grass sward Plots with dung and urine 15 months (1994-1995)	poorly drained silty clay loam	0.359	moisture, pH, soil temperature,soil available NO3-N, NH4-N	5.5	11	-	-	-	1050	Yamulki *et al.*, 1998
Pine forest Sitka Spruce, N inputs 3 yrs (1992-1994)	brown forest soil	0.36	pH, moisture, soil nitrate and ammonium, soil temperature	3.5	11	34 (wt/wt)	-	10	800	Skiba *et al.*, 1996
Birch forest 3 yrs (1992-1994)	brown forest soil	0.6		4.9	10	26 (wt/wt)	-	10	800	Skiba *et al.*, 1996
Mowed grass 3 yrs (1992-1994)	brown forest soil	0.88	soil moisture, pH, available ammonium and nitrate	4.8	11	30 (wt/wt)	-	10	800	Skiba *et al.*, 1996
Alder forest 3 yrs (1992-1994)	brown forest soil	1.32		4.2	9	25 (wt/wt)	-	60	800	Skiba *et al.*, 1996
Riparian zone 12 months (1994-1995)	mostly clayey alluvium	5	water table, groundwater nitrate and ammonium	-	13.08	-	-	-	-	Burt *et al.*, 1999
agricultural Intensively managed 3 yrs (1996-1998)	sandy clay and loam, loam, clay loam	9.35	soil temperature, moisture, SOM, mineral N	-	7.95	66 (wt/wt)	-	330	850	Dobbie *et al.*, 1999

'-' Data not determined or not published
*: typic rendzic leptosol, gleyic luvisol, eutric leptosol
Temperatures are annual means except for the following studies: Henault *et al.*, 1998 (3 months), Martikainen *et al.*, 1994 (9 months), Regina *et al.*, 1996 (9 months)