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Effects of type and amount of applied nitrogen fertilizer on nitrous oxide fluxes from intensively managed grassland

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Abstract

Five field experiments and one greenhouse experiment were carried out to assess the effects of nitrogen (N) fertilizer type and the amount of applied N fertilizer on nitrous oxide (N_2O) emission from grassland. During cold and dry conditions in early spring, emission of N_2O from both ammonium (NH_4^+) and nitrate (NO_3^-) containing fertilizers applied to a clay soil were relatively small, i.e. less than 0.1% of the N applied. Emission of N_2O and total denitrification losses from NO_3^- containing fertilizers were large after application to a poorly drained sand soil during a wet spring. A total of 5–12% and 8–14% of the applied N was lost as N_2O and via denitrification, respectively. Emissions of N_2O and total denitrification losses from NH_4^+ fertilizers and cattle slurry were less than 2% of the N applied. Addition of the nitrification inhibitor dicyandiamide (DCD) reduced N_2O fluxes from ammonium sulphate (AS). However, the effect of DCD to reduce total N_2O emission from AS was much smaller than the effect of using NH_4^+ fertilizer instead of NO_3^- fertilizer, during wet conditions. The greenhouse study showed that a high groundwater level favors production of N_2O from NO_3^- fertilizers but not from NH_4^+ fertilizers. Increasing calcium ammonium nitrate (CAN) application increased the emitted N_2O on grassland from 0.6% of the fertilizer application rate for a dressing of 50 kg N ha^{-1} to 3.1% for a dressing of 300 kg N ha^{-1}. In another experiment, N_2O emission increased proportionally with increasing N rate. The results indicate that there is scope for reducing N_2O emission from grasslands by choosing the N fertilizer type depending on the soil moisture status. Avoiding excessive N application rates may also minimize N_2O emission from intensively managed grasslands.

Introduction

Nitrous oxide (N_2O) is produced in soils through the microbiological processes of nitrification and denitrification (Firestone and Davidson, 1989). The rates of these processes and the rate of N_2O production are dependent on the amounts of ammonium (NH_4^+) and nitrate (NO_3^-) in the soil, as well as other factors. In agricultural soils, there are several sources of NH_4^+ and NO_3^-, including fertilizers, animal wastes, atmospheric deposition, and mineralization of soil organic matter. For NO_3^- containing nitrogen (N) fertilizers, denitrification is initially the only possible direct source of N_2O, whereas both nitrification and denitrification can be involved in the production and emission of N_2O from NH_4^+ containing fertilizers.

A review of field studies by Bouwman (1995) indicates that on average the effect of N fertilizer type on N_2O fluxes is small from agricultural soils. However, in some studies (e.g. McTaggart et al., 1994) larger fluxes have been found from NO_3^- fertilizers than from NH_4^+ fertilizers, whilst in other studies the opposite has been found, particularly from anhydrous ammonia applications, which emitted up to 5% of the amount of fertilizer-N as N_2O (eg. Breitenbeck and Bremner, 1986). The discrepancies between studies suggest that site specific conditions control the N_2O emission from NO_3^- and NH_4^+ fertilizers. Soil moisture status and temperature are probably key factors

Table 1. Overview of experiments.

Experiment	Location	Soil	Period	Treatments*	Design
1	Wageningen	riverine clay	March 1993	Control AS, CN, CAN, UR: 80 kg N ha^{-1}	randomized blocks in 4 replicates
2	Bennekom	poorly drained sand	March - April 1994	Control AS, AS+DCD, CN, CAN, UR: 80 kg N ha^{-1} Cattle slurry surface-applied: 15 m^3 ha^{-1} ** Cattle slurry sod injected: 15 m^3 ha^{-1} **	randomized blocks in 4 replicates
3	Bennekom	poorly drained sand	June - July 1994	Control AS, AS+DCD, CN, CAN, UR: 80 kg N ha^{-1} Cattle slurry surface-applied: 15 m^3 ha^{-1} ** Cattle slurry sod injected: 15 m^3 ha^{-1} **	randomized blocks in 4 replicates
4	Greenhouse	sand	July-Sept. 1994	Two groundwater depths: 15 and 30 cm Control AS, CN: 80 kg N ha^{-1}	split-plot in 3 replicates
5	Bennekom	poorly drained sand	April-May 1994	CAN: 0, 50, 100, 150, 200, 300 kg N ha^{-1} applied in one dressing	randomized blocks in 4 replicates
6	Lelystad	calcareous clay	March-Oct. 1993	CAN: 0, 220, 440, 660, 880 kg N ha^{-1} split in 7 dressings	randomized in 6 replicates

* AS: ammonium sulphate, AS+DCD: ammonium sulphate + nitrification inhibitor DCD, CN: calcium nitrate, CAN: calcium ammonium nitrate, UR: urea

** Mineral N application rate was about 45 kg N ha^{-1}.

because they affect the relative rates of nitrification, denitrification, N_2O production and N_2O consumption (Firestone and Davidson, 1989). Temperature may also affect the relative uptake rate of NH_4^+ and NO_3^- by the sward, thereby possibly indirectly affecting N_2O emission. For example, Watson (1986) showed a preferential uptake of NH_4^+-N over NO_3^--N by ryegrass under cold early spring conditions.

We explored the possibilities for reducing N_2O emission from intensively managed grassland in temperate areas by manipulating the type and the amount of N fertilizer and by the use of a nitrification inhibitor. Soil incubation studies under controlled conditions may provide a good insight in the effects of N type and N rate on N_2O emission from soil (e.g. Bremner and Blackmer, 1978). However, we focused on field and greenhouse experiments on grass, because the soil-root-plant interface may have a tremendous effect on local N, carbon and oxygen availabilities and thereby on N_2O emission (Beck and Christensen, 1987; Smith and Tiedje, 1979).

On intensively managed grasslands a total N application of 200 to 400 kg N ha^{-1} per year is split in 4 to 7 dressings in decreasing amounts, generally. We hypothesized that fewer heavy dressings result in a larger N_2O emission than more frequent lighter dressings. With the lighter dressings, the mineral N content of the soil is lower throughout the growing season (Prins, 1980).

Materials and methods

Three field experiments and one greenhouse experiment were carried out to assess the effects of common N fertilizers on N_2O emission (experiments 1, 2, 3 and 4) and two field experiments (experiments 5 and 6) were carried out to assess the effect of the amount of N fertilizer application on N_2O emission (Table 1). Three experiments (1, 2 and 5) involved springtime conditions, two with summertime conditions (experiments 3 and 4) and one covered the whole growing

Table 2. General properties of the three soils.

Property	Riverine clay Wageningen*	Poorly drained sand Bennekom*	Calcareous clay Lelystad**
Total N, g kg^{-1}	3.7	1.8	2.4
Total C, g kg^{-1}	47	27	27
pH-KCl	5.2	4.8	7.2
Clay content (≤ 2 μm), g kg^{-1}	250	50	295

* 0–10 cm layer
** 0–20 cm layer

season (experiment 6). Soil properties are given in Table 2. In all experiments, fluxes were measured during the daytime, sometime in the period between 9.00 and 13.00 h. Soil temperature at 5 cm depth, rainfall and soil moisture content were determined at regular intervals.

Experiment 1

Experiment 1 was to assess the effect of N fertilizer type on N_2O emission from grassland in early spring. There were four fertilizer treatments and a control (Table 1). Fluxes of N_2O were measured 19 times during 3.5 weeks, following fertilizer applications on 3 March 1993. Fluxes were measured using the flux chamber technique described in detail by Velthof and Oenema (1995). Briefly, fluxes were measured using circular PVC flux chambers with an internal diameter of 20 cm and a height of 15 cm. Concentration of N_2O in the headspace was determined in the field at 0, 10, 20 and 30 minutes after closing the flux chamber, using a photo-acoustic spectroscopic infra-red gas analyzer of Brüel & Kjær. The analyzer was directly attached to six flux chambers via a multipoint sampler in a closed system via tubes. Gas samples were taken and analyzed for N_2O automatically every 90 s after the air in the headspace was pumped around for 20 s. The accuracy of the gas analyzer was about 5% in the range of 300–5000 μl N_2O m^{-3} under field conditions.

Experiments 2 and 3

The effects of type of N fertilizer and cattle slurry on N_2O emission from grassland in spring and summer was assessed in experiments 2 and 3, respectively. The identical experiments 2 and 3 were carried out on a poorly drained sand soil in Bennekom in March-April and June-July 1994, respectively (Table 1). In one treatment the nitrification inhibitor dicyandiamide (DCD) was mixed with AS. Application rate of DCD (67% N) was 20 kg N ha^{-1}. Total application rate of the AS+DCD mixture was 80 kg N ha^{-1}.

The cattle slurry was either surface-applied or injected, to study the effect of application method on N_2O emission. Fresh cattle slurry, obtained from a local farm, was injected with a sod-injector to a depth of 5 cm at a rate of 15 m^3 ha^{-1}, which was equal to a mineral N application rate of about 45 kg N ha^{-1}. Rectangular PVC chambers (width of 30 cm, length of 42 cm and height of 23 cm) were inserted 3 cm into the soil to cover two bands of injected slurry (distance between the slurry bands was 20 cm). The flux chambers have removable lids. Fluxes of N_2O were measured 20 times during 4 weeks in experiment 2 and 22 times during 4.5 weeks in experiment 3, using the system described for experiment 1.

Denitrification rates were measured in duplicate using the acetylene inhibition technique (e.g. Ryden and Dawson, 1982). Denitrification rate was calculated from the amount of N_2O evolved from four undisturbed soil cores of the 0–10 cm soil layer (diameter 4.7 cm), incubated in 3 L incubation containers in an atmosphere with 5% acetylene. The containers were placed in holes in the soil to carry out incubation at soil temperature. The concentration of N_2O in the headspace of the containers was measured after 24 hours using the photo-acoustic infra-red gas analyzer. After the denitrification measurements in experiment 2, the soil cores were dried at 40°C and ground. The concentrations of NO_3^- and NH_4^+ were measured by extraction of 10 g dry soil in 100 ml 0.01*M* $CaCl_2$ and analysis by standard auto-analyzer techniques (Houba et al., 1989).

Experiment 4

Groundwater levels in grassland soils in the Netherlands are often shallow (i.e. within one meter from the

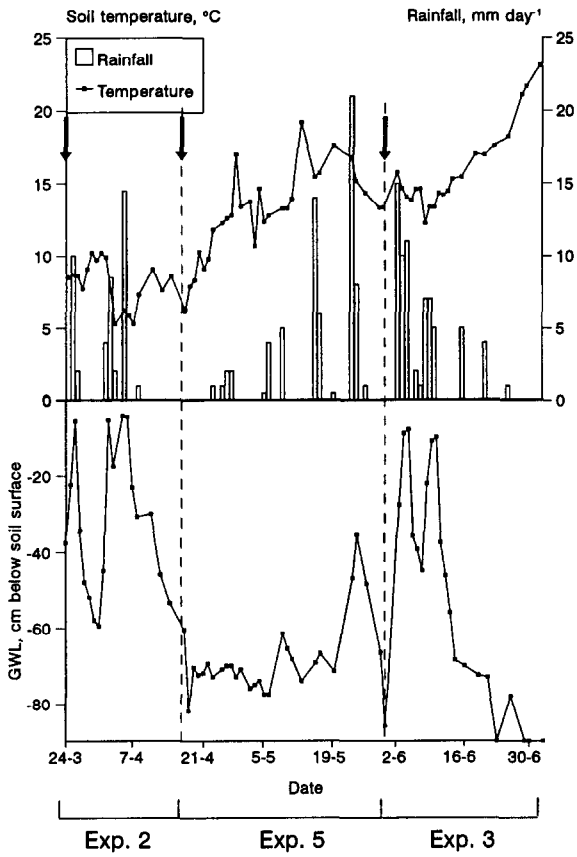

Figure 1. Soil temperature at 5 cm depth, rainfall and groundwater level (GWL) in the poorly drained sand soil in Bennekom in spring of 1994. Arrows indicate the time of N application in the experiments 2, 3, and 5.

soil surface), and are being adjusted to some extent by controlling the water level in ditches surrounding these grasslands. The interaction effect between N fertilizer type and groundwater level on the N_2O emission was examined in a greenhouse experiment. Undisturbed soil cores with an intact sward were taken to a depth of 30 cm from the Bennekom site, using stainless steel columns (internal diameter 20 cm and height 30 cm) with sharp edges. The main factor of the split-plot experiment in three replicates was groundwater level (Table 1). The columns were randomly placed in containers with groundwater levels at 15 and 30 cm below the soil surface. These depths to the groundwater are often observed at the Bennekom site, in the spring and autumn (e.g. Fig. 1). The experiment had two fertilizer treatments, AS and CN at a rate of 80 kg N ha^{-1}, and a control treatment. To simulate rainfall, 2 mm water was added on top of the column, three times a week.

Fluxes of N_2O were measured for almost two months, using the flux chamber technique described for experiment 1. The chambers had a collar of insulation foam and were put over the columns with soil. In total 39 flux measurements were carried out.

Experiment 5

The effect of the amount of N on N_2O emission from grassland in spring was assessed in experiment 5. Fluxes of N_2O were measured after application of calcium ammonium nitrate (CAN: NH_4NO_3 + $CaCO_3$ + $MgCO_3$; 27% N, 6% CaO, 4% MgO) in one dressing of 0, 50, 100, 150, 200 and 300 kg N ha^{-1} on 18 April (Table 1). The study was carried out on the same field as experiments 2 and 3. Fluxes were measured as described for experiment 1. During the first 18 days, flux measurement was carried out daily, except on days 7 and 13. In the period thereafter, the N_2O flux was measured every 2 to 4 days.

Experiment 6

The effect of the amount of N applied on N_2O fluxes from mown grassland during a whole growing season was assessed in experiment 6. Fluxes of N_2O were measured weekly in six replicates from grassland on a calcareous clay soil in the polder close to Lelystad to which CAN was applied at 5 rates; 0, 0.5, 1, 1.5 and 2 times the recommended application rate for each dressing, based on an interactive fertilization system (Vellinga et al., 1996). This recommended rate amounted 440 kg N ha^{-1} for the whole growing season, split in seven dressings: 85, 75, 92, 50, 38, 53, and 47 kg N ha^{-1}, following each mowing and harvesting. The measurement technique was the same as in experiment 1. Flux was measured 29 times between March and November 1993.

Calculations and statistical analyses

Fluxes of N_2O were calculated from the course of the N_2O concentration in the headspace in time, using linear regression analysis. Total N_2O emission was calculated from the time course of the arithmetic mean N_2O flux, by linearly interpolating the mean N_2O fluxes and integrating the area using the trapezoidal method (Velthof and Oenema, 1995). Statistical differences between the treatments were assessed by Analysis of Variance (ANO_3^-VA) and Least Square Difference (LSD) Test (α=0.05), using the statistical pack-

Table 3. Emissions of N_2O, denitrifcation losses (Deni), total rainfall and mean soil temperature at 5 cm depth, for experiments 1, 2 and 3.

N source*	Experiment 1**	Experiment 2**		Experiment 3**	
	N_2O	N_2O	Deni	N_2O	Deni
	% of mineral N applied***				
CAN	<0.1a	5.2c	14.1b	8.3d	8.3b
CN	<0.1a	5.2c	12.4b	12.0d	10.5b
AS	<0.1a	0.2b	0.6a	1.0c	0.0a
AS + DCD	-	<0.1a	0.2a	0.1b	0.0a
Urea	<0.1a	<0.1a	1.1a	0.7c	1.9a
Cattle slurry, surface-applied	-	<0.1a	0.4a	<0.1a	0.4a
Cattle slurry, injected	-	0.1ab	0.0a	<0.1a	0.0a
Total rainfall, mm	13	42		68	
Mean soil temperature, °C	6.0	8.2		16 0	

*N fertilizers were applied at a rate of 80 kg N ha^{-1}, slurries at a rate of 15 m^{-3} ha^{-1} (about 45 kg mineral N ha^{-1}).

**Different letters in each column denote statistically significant differences between treatments ($\alpha = 0.05$).

***Fertilizer-derived N_2O flux in % of the N applied = (N_2O-N fertilized grassland - N_2O-N unfertilized grassland) (amount of N applied) × 100

age Genstat 5.0 (Genstat 5 Committee, 1987). Prior to the statistical analyses, fluxes of N_2O were log-transformed to stabilize variance.

Results

Experiment 1

Application of both NH_4^+ and NO_3^- fertilizers increased the N_2O flux from grassland on the clay soil in early spring (data not shown). However, fluxes were low, less than 0.1 mg N m^{-2} hr^{-1}, and there were no significant differences in N_2O flux between the mineral N fertilizers. Total emissions during the experimental period were less than 0.1% of the N applied as mineral N fertilizer (Table 3). These small emissions were probably due to the cold (mean soil temperature 3.5 °C) and dry (< 3 mm rainfall) conditions during the first half of the experimental period.

Experiment 2

During the first three days, the groundwater depth in the poorly drained sandy soil rose from about 40 cm to 5 cm below the surface, following heavy rainfall (Fig. 1). A temporary drop in the groundwater depth between days 2 and 6 was followed by a rapid rise to about 5 cm below the soil surface again after heavy rainfall. Soil temperatures during the experimental period were below 10 °C (Fig. 1).

The fluxes of N_2O and the rates of denitrification from the different fertilizers peaked after 2–3 days after N fertilizer application (Figs. 2A and 2C). Fluxes were much larger from CN and CAN than from AS. Fluxes from cattle slurry and urea were very low, and similar to those from AS (data not shown). The patterns of N_2O fluxes and denitrification rates were related to NO_3^- contents (Fig. 2B) and not to NH_4^+ contents in the soil (Fig. 2D). About 3 to 4 weeks after N application, mineral N contents of the fertilized grasslands were similar to the unfertilized, and N_2O fluxes and denitrification rates were low.

Total N_2O emission from CN and CAN were relatively large, i.e. 5.2% of the N applied (Table 3). More than 10% of the N applied as CAN and CN was lost by denitrification (Table 3). By contrast, emission of N_2O from the NH_4^+ fertilizers were < 0.2% of the N applied, and total N losses via denitrification < 1.1%.

Experiment 3

The groundwater depth in the poorly drained sandy soil rose from about 80 cm to 10 cm following heavy rainfalls during the first week after N fertilizer application (Fig. 1). The soil temperature increased from about 13 °C during the first week to more than 20 °C during the last days of the experiment (Fig. 1).

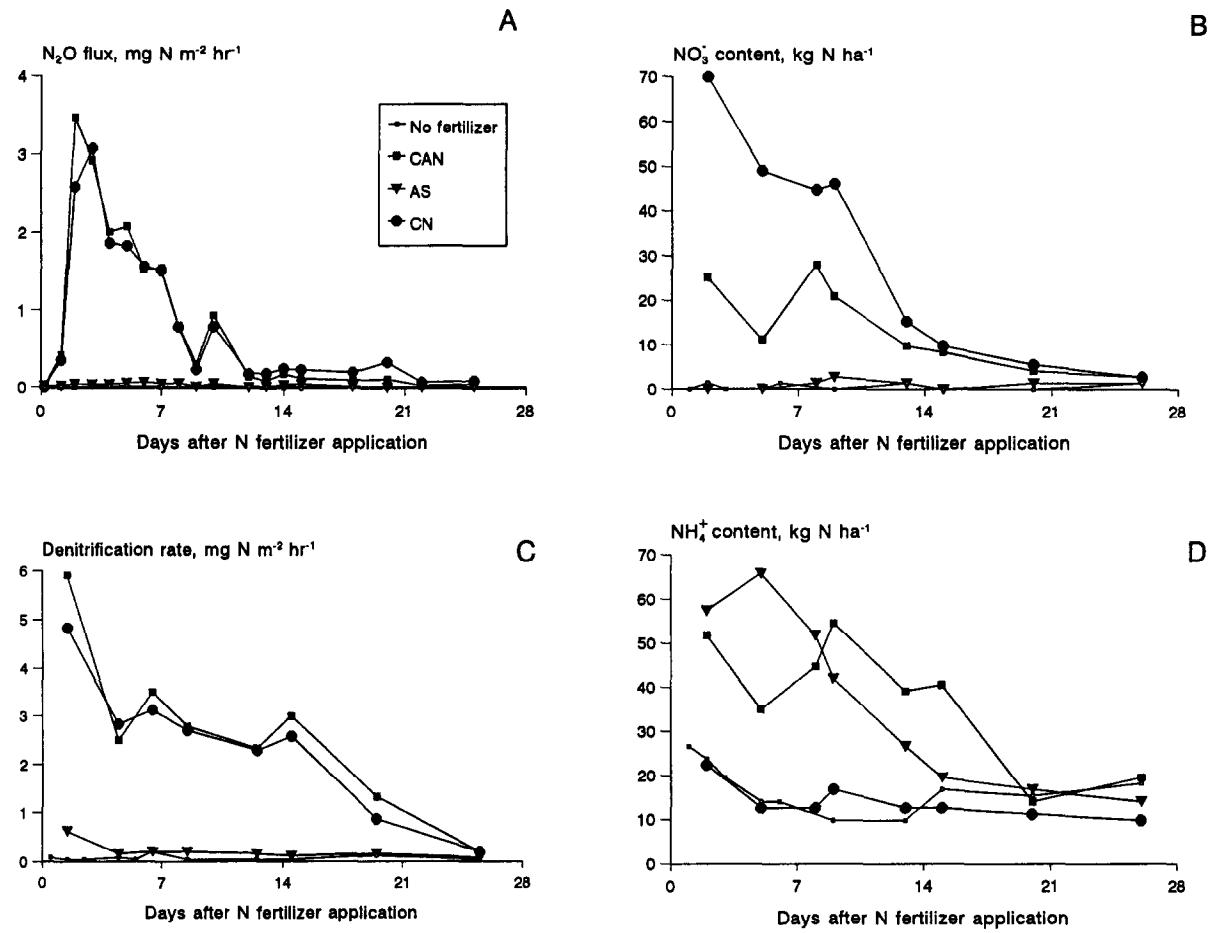

Figure 2. Rate of N_2O flux (A), NO_3^- content (B), denitrification rate (C) and NH_4^+ content (D) for unfertilized and N fertilized grassland (experiment 2).

The fluxes of N_2O and the rates of denitrification were much larger from CN and CAN than from AS and cattle slurry (Figs. 3A, B and C). The fluxes of N_2O from CN and CAN were similar to denitrification rates in terms of N loss (Figs. 3B and 3C), indicating that N_2O was by far the major end product of denitrification. Fluxes of N_2O were sometimes higher than the denitrification rates, despite the fact that the data indicate that the N_2O orginated predominantly from denitrification. The higher N_2O fluxes compared to denitrification rates are probably due to the facts that i) spatial variability of both processes was large and that ii) the measurement of N_2O fluxes and denitrification rates were carried out on different plots.

The N_2O peak fluxes from AS, AS+DCD and cattle slurry occurred during the first three days (Fig. 3A), and coincided with the rainfall events and the concomitant rise in groundwater depth (Fig. 1). These peak fluxes were probably related to denitrification activity and gas displacement by the rising water. Between days 3 and 25, fluxes were larger from AS than from AS+DCD, cattle slurry and the control treatment.

The total N_2O emission from CN and CAN treatments were very large; 8.3% of the N applied as CAN and 12.0% of the N applied as CN escaped as N_2O (Table 3). The emissions of N_2O-N and the N losses by denitrification were similar (Table 3). The emissions of N_2O from AS, AS + DCD, urea and the slurries were less than 1.0% of the amount of fertilizer N, and emissions from AS+DCD were significantly less than those from AS.

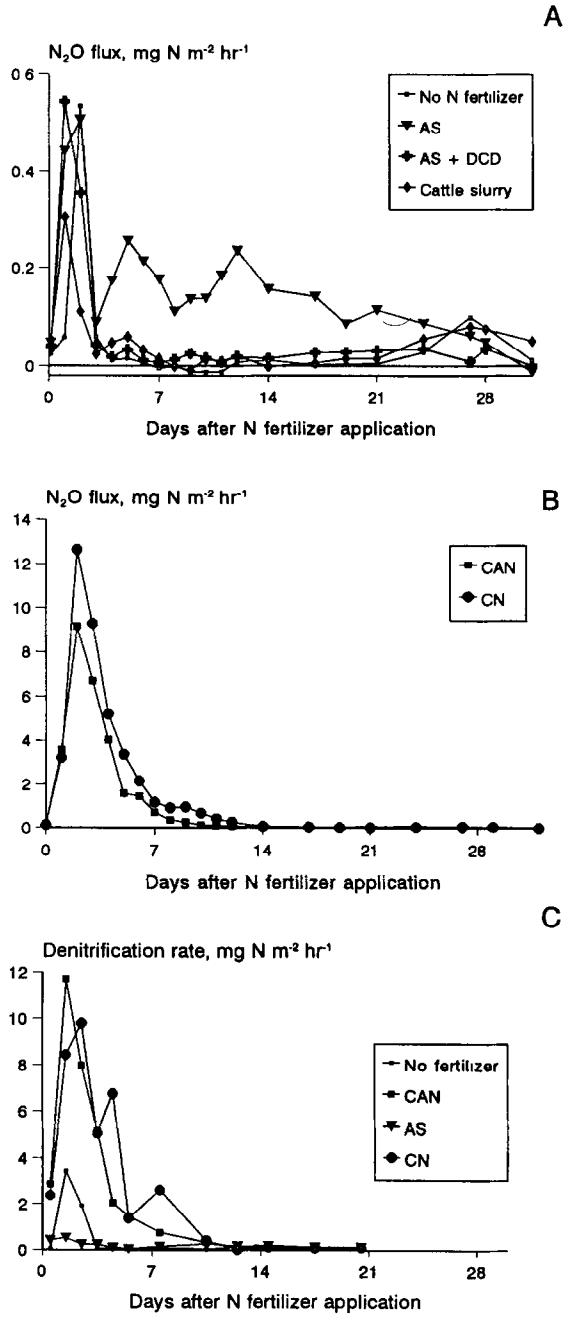

Figure 3. Rates of N_2O flux from control and NH_4^+ fertilizers (A) and from NO_3^- fertilizers (B) and denitrification rates (C) (experiment 3) Note differences in scale of Y-axes.

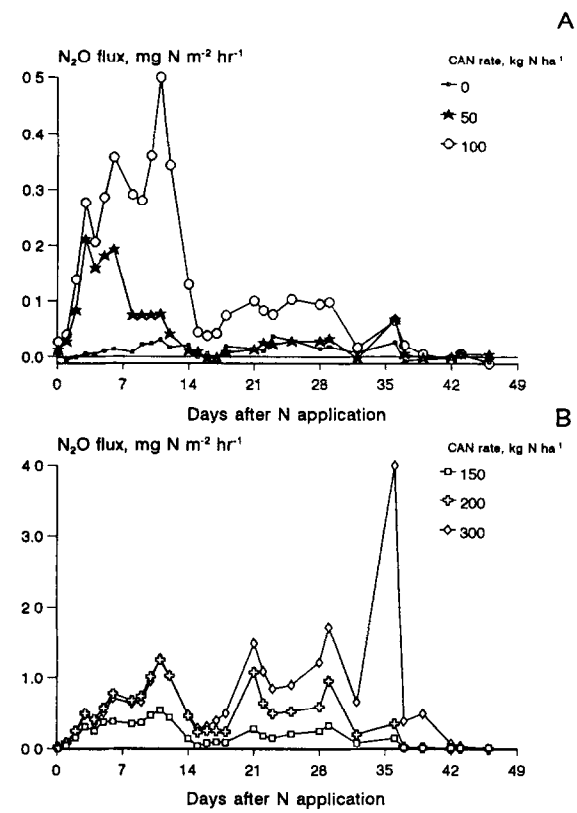

Figure 4. Rates of N_2O flux after application of CAN to grassland at rates of 0, 50 and 100 kg N ha^{-1} (A) and 150, 200 and 300 kg N ha^{-1} (B) (experiment 5). Note differences in scale of Y-axes.

Experiment 4

The greenhouse experiment on the interaction effect between N fertilizer type and groundwater depth was carried out under warm conditions, with the soil temperature at 5 cm ranging from 20 to 27 °C. Grass growth was restricted during the experiment, probably because of the high soil temperatures. Fluxes from CN were larger when the groundwater depth was at 15 cm than when it was at 30 cm (data not shown). In contrast, fluxes from AS were larger for a groundwater level of 30 cm than for a level of 15 cm (data not shown). Peak fluxes of 9.8 mg N m^{-2} hr^{-1} occurred at one day after CN application and peak fluxes of 0.3 mg N m^{-2} hr^{-1} occurred 9 days after AS application (data not shown). The duration of fertilizer-derived N_2O flux was much longer for the groundwater level of 30 cm than for the groundwater level of 15 cm, for both AS and CN (Table 4). The order in the total N_2O emission was: no fertilizer < AS < CN, for both groundwater levels (Table 4).

Table 4. Emission of N_2O related to fertilizer type and depth to groundwater table for the greenhouse experiment (Experiment 4).

Fertilizer	Depth to groundwater, cm	Duration of fertilized-derived flux, days*	Total N_2O emission**	
			kg N ha^{-1}	% of N applied
Control	15	-	0 35a	-
	30	-	0 17a	-
AS	15	21	1.09b	0.9
	30	48	1.30b	1.4
CN	15	11	9.39d	11.3
	30	40	5.03c	6.1

*number of days in the 60-day period that N_2O flux from the fertilized treatments was significantly ($\alpha = 0.05$) larger than the N_2O flux from the control treatment.
**Different letters denote statistically significant differences between treatments ($\alpha = 0\ 05$)

Experiment 5

The amount of the fertilizer applied affected both the flux magnitude and duration, i.e. the heavier the N application, the larger the peak flux and the longer the duration of the flux (Figs. 4A and B). Fluxes of N_2O increased after rainfall, especially for the heavier N application rates (Figs. 1 and 4). A peak flux was found for the unusually heavy dressing of 300 kg N ha^{-1} five weeks after N application at 18 April, during a relatively wet and warm period (Figs. 1 and 4).

Total N_2O emission increased with an increase in the amount of N application (Fig. 5A). The percentage of the N applied which was lost as N_2O increased from 0.6% for a dressing of 50 kg N ha^{-1} to 3.1% for 300 kg N ha^{-1}.

Experiment 6

Generally, the fluxes from the clay soil were relatively small (i.e. less than 0.1 mg N m^{-2} hr^{-1}) during the growing season for all N application rates, except after the third N application when peak N_2O fluxes up to 1.5 mg N m^{-2} hr^{-1} were measured (data not shown). Total N_2O emission during the growing season increased from 0.5 to 4.7 kg N ha^{-1}, when total N application rate increased from 0 to 880 kg N ha^{-1} (Fig. 5B). The percentage of N emitted as N_2O was relatively small; 0.4% for a total N application rate of 220 kg N ha^{-1} and 0.5% for application rates of 440, 660 and 880 kg N ha^{-1} (Fig. 5B).

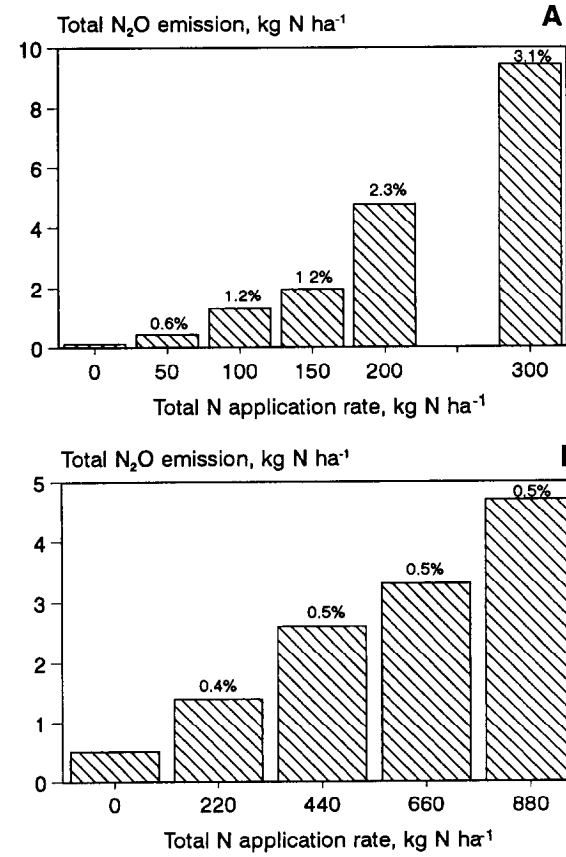

Figure 5 Relationship between total N application rate and total N_2O emission from grassland. (A· experiment 5 and B experiment 6). Percentages indicate the percentage of applied fertilizer N emitted as N_2O

Discussion

Effect of fertilizer type on N_2O flux

The relatively small N_2O emission from the clay soil in early spring (experiment 1) suggest that the cold and dry soil conditions did not favor N_2O production. By contrast, the extremely large N_2O fluxes in the first 8 days from CN and CAN (experiments 2 and 3) indicate that the wet conditions favoured N_2O emission from the poorly drained sandy soil. The much larger N_2O emission from the NO_3^- fertilizers than from the NH_4^+ fertilizers indicate that denitrification was by far the major source of N_2O during wet conditions in the poorly drained sand soil (experiments 2 and 3). This was confirmed by the denitrification rates which were much higher for the NO_3^- fertilizers than for the NH_4^+ fertilizers (Figs. 2 and 3 and Table 3). The denitrification rates for the NH_4^+ fertilizers may have been slightly underestimated in case denitrification rate was dependent on the release of NO_3^- from nitrification of fertilizer NH_4^+. This is so because acetylene also inhibits nitrification (e.g. Aulakh et al., 1984). However, the low NO_3^- concentrations and the high NH_4^+ concentrations in the NH_4^+ treated soil (Fig 2), indicate that nitrification was slow anyway, due to the wet conditions in the field. Generally, NO_3^- concentrations are much higher than NH_4^+ concentrations in grassland soils in the Netherlands.

The lower emission from AS+DCD than from AS indicates that the nitrification inhibitor reduced N_2O fluxes from NH_4^+ fertilizers, as also indicated by e.g. McTaggart et al. (1994) and Skiba et al. (1993). However, the effect of DCD to reduce the total N_2O emission from AS was much smaller than the effect of using NH_4^+ fertilizer instead of NO_3^- fertilizer (Table 3). Groundwater fluctuations had a tremendous effect on N_2O flux from fertilizers, and especially from NO_3^- sources (Experiment 4).

McTaggart et al. (1994) found a much larger emission from urea than from AS, suggesting that hydrolysis of urea and associated pH increase stimulated N_2O production. Probably, ammonia inhibits the oxidation of nitrite (NO_2^-) to NO_3^- by *Nitrobacter*, resulting in NO_2^- accumulation and enhanced N_2O production. This is supported by the much higher N_2O fluxes from anhydrous ammonia than from other N fertilizers (eg. Breitenbeck and Bremner, 1986). In contrast, similar N_2O emission from urea and AS were found in experiments 1, 2 and 3 (Table 3). We suggest that the cold conditions in experiment 1 and the very wet conditions in experiments 2 and 3 reduced the increase in soil pH due to urea hydrolysis, causing emission from urea and AS to be similar.

Experiments 1–4 indicate that the use of NH_4^+ fertilizer instead of NO_3^- fertilizers may greatly reduce N_2O emission and denitrification losses from grasslands during wet conditions. Similar results were found by McTaggart et al. (1994) for N_2O emission and by Jordan (1989) and Ryden (1984) for denitrification losses from intensively managed grasslands. Peak N_2O fluxes and denitrification rates are generally found during the first few days after N application, when mineral N content is highest (eg. Figs. 2 and 3). Thereafter, mineral N content in the soil strongly decreases due to the rapid N uptake by the sward. This indicates that there is scope for reducing N_2O emissions from intensively managed grasslands by choosing the N fertilizer type depending on the soil moisture status in combination with the expected rainfall and evapotranspiration during the next few days. Such a fertilization strategy should take into account also other effects of fertilizer type, like the effects on mineral composition of the grass, ammonia (NH_3) volatilization, soil acidification and botanical compostion of the sward (e.g. Van Burg et al., 1982).

Fluxes of N_2O from cattle slurry

Fluxes of N_2O from cattle slurry were small and were not affected by the application method. As pointed out before, the much larger emissions from the NO_3^- fertilizers than from the NH_4^+ fertilizers, including cattle slurry, were due to the very wet conditions which favoured denitrification. The lower application rate of mineral N via the cattle slurries (about 45 kg N ha^{-1}) than via the mineral N fertilizers (80 kg N ha^{-1}) may have contributed to the lower N_2O emissions from the cattle slurries than from the NH_4^+ fertilizers (Table 3 and Fig. 3). Egginton and Smith (1986) and Velthof and Oenema (1993) also found much lower N_2O emission from slurry than from ammonium nitrate (AN) or CAN. By contrast, N_2O emission from slurry treated grassland were larger than from AN treated grassland in the study by Christensen (1983). Granli and Bøckman (1994) suggested that emission of N_2O is larger from organic manures than from mineral N fertilizers after application to soils in which the availability of organic C is limiting the denitrification rate and that the opposite is shown for soils in which organic C does not limit the denitrification rate. The much larger emission from CN and CAN than from the cattle slurry in the present

study suggests that availability of organic C was not limiting the denitrification rate in the grassland soil.

Present laws in the Netherlands, require farmers to use slurry application techniques that minimize NH_4^+ volatilization, like sod-injection, deep-injection, and trailing-feet (Huijsmans et al., 1996). These techniques differ in the way in which slurry is in contact with soil and also differ in the ease with which N from the slurry can be taken up by the grass roots. The present study shows no clear effect of slurry application technique on N_2O emission. However, both experiments were carried out under extremely wet conditions. Further studies are needed to assess the effects of application technique on N_2O emission from slurry.

Effect of application rate of N fertilizer on the N_2O flux

The pattern of N_2O flux after application of CAN in amounts of 0 to 300 kg N ha^{-1} in experiment 5 is related to interactions of the amount of N application, N uptake by the sward and soil moisture (Figs. 1 and 4). Applications of more than about 100 kg N ha^{-1} likely exceeded the uptake capacity of the sward, by which mineral N contents of the top soil remained high for 3 to 5 weeks. By contrast, the flux of N_2O remained small from day 14 onwards when N application did not exceed 100 kg N ha^{-1}. Obviously, the fertilizer N applied at a low rate was taken up rapidly by the sward, keeping the mineral N contents in the soil low.

The relationship between N application and total N_2O emission had an exponential shape (Fig. 5A), confirming our hypothesis that one heavy application may result in much larger N_2O emissions than split dressings of an equal total N application. The results of this experiment substantiate those of Ryden (1983) showing that increasing the N application rate increases the percentage of fertilizer N emitted as N_2O. Similar results were found by Garret et al. (1992) for denitrification losses from grasslands. However, the results of experiment 6 do not show this effect (Fig. 5B). A factor which may have contributed to the apparently linear relationship between N input and N_2O emission is the high N uptake capacity of this particular sward and the large apparent recovery of fertilizer N at this site, even at N application rates up to 700 kg N ha^{-1} yr^{-1} (e.g. Deenen and Lantinga, 1991). Another factor that may have contributed to the relatively small N_2O emission at high N application rates at this site is the apparent immobilization of fertilizer N into the soil organic matter pool. The organic matter content of this recently reclaimed soil is increasing and up to 245 kg N ha^{-1} per year can accumulate in the soil organic matter pool (Hassink and Neeteson, 1991).

Conclusions

The results of these studies and those of McTaggart et al. (1994), Jordan (1989) and Ryden (1984) indicate that there is scope for reducing N_2O emission and denitrification losses from grasslands using a fertilization strategy in which the choice of N fertilizer type is dependent on the soil moisture status in combination with the expected rainfall and evapotranspiration during the next few days. Moreover, the present study also indicates that preventing excess N applications and splitsing of N applications may minimize N_2O emission from intensively managed grasslands. Hence, further refinement of N fertilizer recommendations may result in a progressive reduction of N_2O emission from grassland.

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