

Nitrous oxide flux from nitric-acid-treated cattle slurry applied to grassland under semi-controlled conditions

G.L. VELTHOF & O. OENEMA

NMI, Department of Soil Science and Plant Nutrition, Wageningen, Agricultural University, P.O. Box 8005, NL 6700 EC Wageningen, Netherlands

Received 7 October 1992; accepted 4 February 1993

Abstract

Nitrous oxide (N_2O) fluxes from cattle slurry after surface application to grassland were measured under semi-controlled environmental conditions during three periods in 1991. Three types of cattle slurry were examined: untreated slurry and slurries treated with nitric acid (HNO_3) to pH 6.0 and 4.5. Treatment with HNO_3 is a proposed technique to reduce ammonia volatilization from slurry during storage, and during and after surface application. N_2O flux was determined one to four times a day for 7 to 18 days after application of 0.64 to 3.8 kg slurry m^{-2} . Slurry-derived fluxes were much higher from treated slurries than from untreated slurries. Cumulative N_2O losses ranged from less than 0.2 % of the mineral N applied via untreated slurry to a maximum of 3.4 % of mineral N for treated slurry of pH 6.0, which was stored for one week before application. N_2O fluxes from slurry of pH 6.0 and those from slurry of pH 4.5 were similar, provided that the pH-6.0 slurry was treated one hour before application. Differences between treatments with treated slurry and those with calcium ammonium nitrate were relatively small; apparently the amount of NO_3^- N applied controlled the N_2O flux. Regular irrigation strongly increased N_2O fluxes.

Keywords: nitrous oxide, grassland, cattle slurry, treated cattle slurry, nitric acid

Introduction

One of the measures to reduce ammonia (NH_3) emission from animal slurries is the acidification of these slurries. Studies in the United Kingdom have shown that acidification of animal slurry to pH 5.5-6.0 with sulphuric acid (H_2SO_4) reduced NH_3 losses by 30-95 % after surface application (Frost et al., 1990; Pain et al., 1990; Stevens et al. 1989; 1992). Similar results were obtained by Bussink & Bruins (1992) for slurries treated with nitric acid (HNO_3). Addition of HNO_3 also increases the fertilizer value of the slurry because the entrapped NH_3 and added nitrate (NO_3^-) are both directly available for uptake by plants.

However, addition of HNO_3 to generally anaerobic and carbon-rich slurry may promote denitrification, the microbial reduction of NO_3^- into gaseous nitrous oxide (N_2O) and dinitrogen (N_2) (Firestone & Davidson, 1989). Denitrification leads to a loss of plant available N and also to an increase in slurry pH (Oenema & Velthof, 1993). Furthermore, there may be an increased emission of N_2O as it is one of the

volatile products of denitrification. Indeed, N_2O fluxes from cattle slurry treated with HNO_3 were much higher than those from untreated slurry during storage for up to six months (Oenema & Velthof, 1993). N_2O is suspected of a probable contribution to global warming and to destruction of ozone in the stratosphere (Bouwman, 1990). The aim of the experiments described here was to determine the N_2O flux from grassland after surface application of untreated slurry and slurries treated with HNO_3 to pH 6.0 and 4.5.

Currently, two variants of the slurry acidification procedure are tested in practice, i.e. acidification to pH 6.0 just before surface application and acidification to pH 4.0 to 4.5 immediately after deposition of the slurry by the cattle in the barn. In the latter variant, the HNO_3 treated slurry may be stored for up to 6 months before surface application. Slurries of both variants, with some modifications, were examined.

A soil cover chamber technique was chosen to measure the N_2O flux, because this technique is most appropriate for measuring small areas that are manipulated by fertilization (Mosier, 1989). A major problem in making reliable estimates of the flux from (un)fertilized grassland, based upon chamber measurements, is spatial variability. We assumed that this problem could be reduced by using a newly established sward on homogeneous soil in columns in which the groundwater level was fixed. We also assumed that irrigation increases soil moisture content and, thereby, N_2O flux.

Materials and methods

Materials

Measurements were carried out with cattle slurries in three experiments during periods from 10 to 17 June, 21 to 30 August and 30 September to 17 October 1991. The slurries were applied to a grass sward in stainless steel columns (internal diameter 20 cm, height 30 cm). Each column contained 12 kg sandy soil with a pH (KCl) of 4.74, 7.05 % organic matter, 4.6 % clay, 10.3 % silt, 59.1 % fine sand and 26.0 % coarse sand. *Lolium perenne* L. was the dominant grass species in the one-year-old sward. The columns were placed in the open, on a dish with 2 cm of water to keep the soil moisture status constant. During nights and during periods of rainfall, a mobile greenhouse covered the columns.

Cattle slurry was obtained from a local dairy farm. The slurry was acidified to pH 6.0 and 4.5 with 10.3 M HNO_3 . In the first experiment, the slurry was acidified one week before application. In the second and third experiments slurries of pH 6.0 were acidified one hour and those of pH 4.5 one week before application. During storage at 15 °C for one week, the slurries were homogenized regularly and the pH was kept at the target pH by addition of HNO_3 if necessary. The untreated slurry was also homogenized regularly.

Concentrations of NH_4^+ , NO_3^- and N_2O in the slurries were measured according to the procedures described by Oenema et al. (1993). The chemical composition and application rates of the slurries in all three experiments are given in Table 1. The homogenized slurries were applied with a pipette to the sward, which was cut one day before application.

NITROUS OXIDE FLUX FROM NITRIC-ACID-TREATED CATTLE SLURRY

Experimental design

The first two experiments had a split-plot design with treatments in four replicates. Irrigation was the main factor. There were five treatments in type and rate of slurry: untreated slurry, treated slurry of pH 6.0, treated slurry of pH 4.5 at two application rates and a control. All these treatments were carried out with and without irrigation. When irrigated, treatments received about 5 mm water per day from a sprinkler installation. N₂O flux was measured once a day between 9.00 and 12.00 a.m., for 7 to 9 consecutive days.

The third experiment had a randomized block design with treatments in four replicates. The treatments were: untreated slurry, treated slurries of pH 6.0 and 4.5, calcium ammonium nitrate (CAN), a control and an additional treatment in which treated slurry of pH 4.5 was applied to inert quartzitic sand without a grass sward. The latter treatment was included to determine the effect of soil and sward on N₂O flux. All treatments were irrigated every two days with 5 mm water. N₂O fluxes were measured four times a day during the first four days, usually starting at 3.00 and 9.00 a.m., and at 3.00 and 9.00 p.m.; thereafter one to two times per day, starting at 9.00 a.m. and 15.00 p.m.

Flux measurements

Measurements were carried out with vented closed chambers (Mosier, 1989). The circular PVC chambers (internal diameter 25 cm and height 10 cm) had a collar of insulation foam attached to the bottom to minimize gas exchange with the outside atmosphere. The flux was calculated from the increase in N₂O concentration in the headspace of the chambers with time. Slurry-derived N₂O flux was calculated by subtracting the average N₂O flux from the unfertilized control treatment.

In experiment I, the headspace of the chambers was sampled with 12 ml polypropylene syringes via rubber septa in the lid three times, usually after 0, 30 and 60 minutes. All samples were analyzed by gas chromatography within two days after sampling.

Because of the time consuming procedure and the possible errors introduced via sampling and sample storage, N₂O was measured with a photo-acoustic infra-red gas analyzer in experiments II and III. The analyzer was directly attached to the chambers, using polytetrafluorethylene tubes (internal diameter 0.3 cm, length 75 cm) with traps of soda lime and magnesium perchlorate to remove CO₂ and H₂O, respectively. A gas sample was taken and analyzed for N₂O automatically about every minute, after the air in the headspace of the chamber was pumped around for 30 s at a flow rate of 30 ml s⁻¹. All 5 or 6 treatments within one replicate were measured sequentially. This procedure was repeated four or five times, so that all treatments were measured four or five times at regular time intervals during an enclosure period of 30 to 40 minutes. Immediately thereafter, the treatments in the other three replicates were measured sequentially.

The increase in the N₂O concentration in the headspace was linear with time. Generally, the linear correlation coefficient (r^2) was ≥ 0.98 and the precision of the

calculated flux was high. However, if the N₂O concentration increased less than about 3 ppbv per minute and the flux was less than about 0.03 mg N m⁻² hr⁻¹, r² was usually less than 0.98 (Fig. 1). Thus, the precision of the calculated flux increased with increasing flux. The unit ppbv is equivalent to μl m⁻³.

Analytical procedures

NO₃⁻ and NH₄⁺ were analyzed by standard auto-analyzer methods (Technicon: US no 824-87T and US no 795-86T, respectively). N₂O was measured via a PU 4400 gas-chromatograph equipped with 27.5 m Porapak Q wide bore column and a ⁶³Ni electron capture detector (ECD) or via a photo-acoustic spectroscopic Gas Monitor Type 1302 of Brüel & Kjær, equipped with the optical filters UA 0982, UA 0985 and SB 0527. Analysis of gas standards with N₂O concentration in the 300-1000 ppbv range, showed that the accuracy of the N₂O analyses was within 5 % when measured with the gas monitor in the field.

Results and discussion

Composition of slurries

The large differences in slurry composition (Table 1) were due to slurry origin and treatment. The initial pH, dry matter and NH₄⁺ contents, and acid neutralizing capacity of the slurry of experiment I were higher than those of the slurries of experiments II and III. Differences between slurries within one experiment were the result of slurry acidification. Addition of HNO₃ increased the NO₃⁻ content and decreased NH₃ volatilization so that treated slurries had higher NH₄⁺ contents than untreated

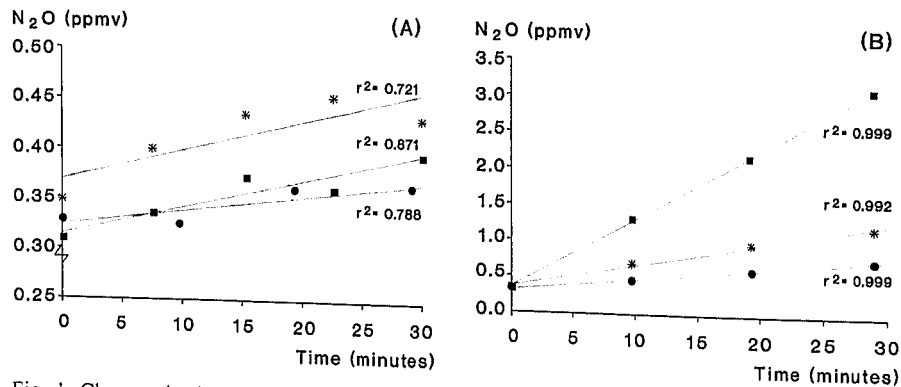


Fig. 1. Changes in the N₂O concentration in the headspace of vented closed chambers on a fertilized grass sward with time, illustrating the effect of flux rate on precision of the flux. Relatively low concentration increases and a corresponding low linear correlation coefficient (r²) are shown in A; rapid increases and high r² in B. The N₂O concentration was measured with a photo-acoustic infra-red gas analyzer directly attached to the chamber.

NITROUS OXIDE FLUX FROM NITRIC-ACID-TREATED CATTLE SLURRY

Table 1. Some chemical properties and application rates of the slurries. Samples were taken just before application to the grass sward.

Expt	Slurry	pH	Dry matter (g kg ⁻¹)	NH ₄ ⁺ -N (g kg ⁻¹)	NO ₃ ⁻ -N (g kg ⁻¹)	N ₂ O-N (mg kg ⁻¹)	Application rates (kg m ⁻²)
I	Untreated	7.4	110	2.18	0.02	0.02	1.27
	pH 6.0*	6.0	113	2.40	1.94	6.34	1.27
	pH 4.5*	4.4	123	2.79	4.41	0.07	0.64 1.27
II	Untreated	7.0	90	1.32	0.00	0.01	1.27
	pH 6.0**	6.0	108	1.82	1.19	0.41	1.27
	pH 4.5*	4.5	109	1.89	3.58	0.13	0.64 1.27
III	Untreated	6.9	112	1.91	0.00	-***	3.82
	pH 6.0**	6.0	-	2.23	1.32	-	2.22
	pH 4.5*	4.5	-	2.51	4.07	-	1.27
	CAN	-	-	13.50	13.50	-	0.03

* Slurry acidified one week before application. ** Slurry acidified one hour before application. *** Not analyzed.

slurries, which contained no or only traces of NO₃⁻.

The dissolved N₂O content of the pH-6.0 slurry was 15 times higher in the first experiment than in the second experiment (Table 1). Apparently, N₂O accumulated in the slurry during storage for one week in the first experiment. The relatively low N₂O contents in the untreated and in the pH-4.5 slurries suggest that N₂O production rate was low in these slurries. Under conditions favourable for denitrification up to 500 mg N₂O-N per kg slurry can accumulate in slurries of pH 6.0 (Oenema & Velt-hof, 1993).

Variability of N₂O fluxes

Fluxes of N₂O were rather low during most measurements, but in some treatments and on some dates, the flux was very high. The frequency distributions of the fluxes in the three experiments were highly skewed and lognormal.

The coefficient of variation of the average flux of four replicates ranged from 4 to 200 % with an average of 83 % (Fig. 2). A high coefficient of variation is typical for N₂O fluxes from grassland and other terrestrial systems, when measured with a flux chamber technique (Mosier, 1989). In an attempt to reduce the variability within treatments we performed the measurements under semi-controlled conditions, using thoroughly homogenized sandy soil with a uniform and constant soil moisture status. However, the results of this study suggest that the within-treatment variability may be also large in columns with uniform sward and treatment. Probably, slight differences between columns in percolation rate may have increased the variability. The variability within treatments remained high throughout the experimental period; columns with a relatively high flux at the start of the experiment kept a strong source

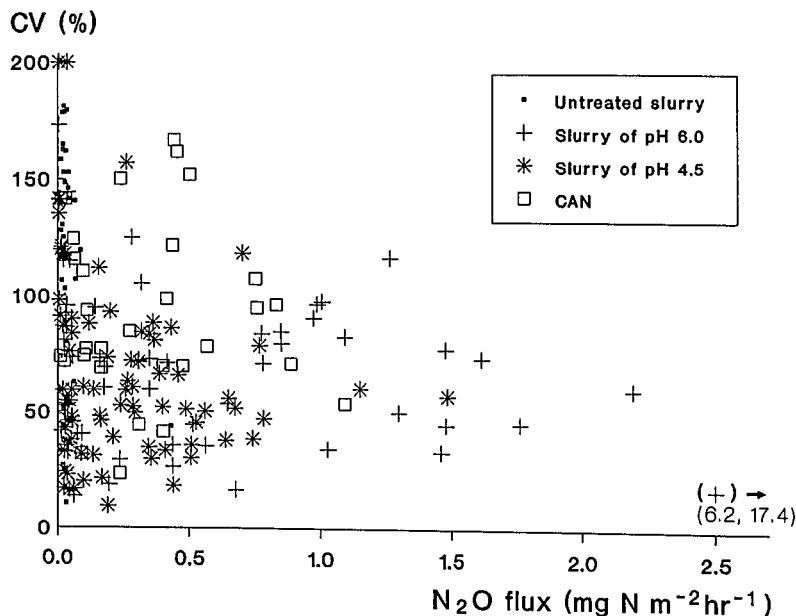


Fig. 2. Mean N_2O fluxes versus coefficients of variation (CV). Means and CVs were obtained from four flux measurements.

strength; low initial rates remained low.

Type of slurry and fertilizer did not clearly affect the coefficient of variation. Coefficients of variation slightly decreased with an increase in the N_2O flux (Fig. 2).

N₂O fluxes: experiments I and II

Fluxes of N_2O from the control treatments were usually lower than $0.01 \text{ mg N m}^{-2} \text{ hr}^{-1}$. Slurry-derived fluxes from treatments with untreated slurry were also low, i.e. less than $0.04 \text{ mg N m}^{-2} \text{ hr}^{-1}$ in both experiments. Slurry-derived fluxes were 1 to 2 orders of magnitude higher from HNO_3 treated slurries than from untreated slurry in both experiments and for both pH levels.

There are two main biological sources of N_2O , viz. denitrification and nitrification (Firestone & Davidson, 1989). The fact that N_2O flux was high after application of treated slurry and low after application of NO_3^- free untreated slurry suggests that denitrification was the dominant source of N_2O in the experiments. Nitrification of slurry NH_4^+ , possibly in combination with subsequent denitrification, was a minor source of N_2O , as total amounts of N_2O emitted after application of untreated slurry were low.

The mean flux from the pH 6.0 treatment was much higher in the first than in the second experiment (Fig. 3). This could be an effect of the duration of slurry treatment before application; in experiment I, HNO_3 was added one week, and in experiment II, one hour before application. Apparently, the denitrifying population was

NITROUS OXIDE FLUX FROM NITRIC-ACID-TREATED CATTLE SLURRY

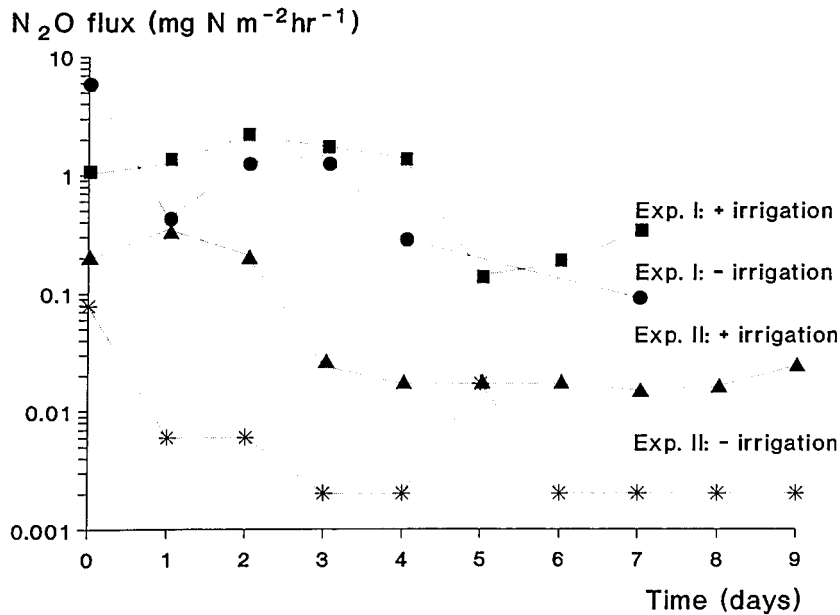


Fig. 3. Slurry-derived N₂O fluxes from treated cattle slurry of pH 6.0 applied at a rate of 1.27 kg m⁻² to the surface of a grass sward with and without daily irrigation. Means of four replicates, from experiments I and II. Note logarithmic scale of Y axis.

much more active one week after addition of HNO₃ than one hour after addition. The fact that the concentration of dissolved N₂O was higher in the one-week-old than in the one-hour-old pH-6.0 slurry (Table 1) supports this suggestion, just as the large flux immediately after application of one-week-old slurry (Fig. 3).

In experiment I, N₂O flux was lower from the pH 4.5 treatment than from the pH 6.0 treatment (Table 2). In experiment II, fluxes showed little variation, indicating that slurry acidified to pH 6.0 one hour before application behaved similar to one-week-old slurry of pH 4.5.

An increase in application rate from 0.64 to 1.27 kg m⁻² increased the flux from the pH 4.5 treatment (Figure 4). This agrees with the conclusion of Eichner (1990) and Bouwman (1990) that N₂O fluxes generally increase with increasing N application rate.

Irrigation increased N₂O fluxes from all treatments in experiments I and II (Fig. 3). In some treatments irrigation increased fluxes by more than one order of magnitude. The effect of irrigation may suggest that denitrification was the dominant source of N₂O. Water in slurry and soil may act as a barrier to oxygen (O₂) diffusion and may stimulate microbial consumption of trapped O₂, resulting in reducing conditions and increased denitrification in slurry and soil.

Table 2. Summed slurry- and CAN-derived N_2O losses ($mg\ N\ m^{-2}$) and as a percentage of mineral N and NO_3^- -N applied during the three experiments.

Expt	Treatment	N application rate		Regular irrigation	N_2O -N emitted		
		mineral ($g\ m^{-2}$)	NO_3^- ($g\ m^{-2}$)		$mg\ m^{-2}$	% of N applied	
						mineral	NO_3^- -N
I	Untreated	2.8	0.0	-	<2	<0.1	
				+	<3	<0.2	
	pH 6.0	5.6	2.5	-	163	2.9	6.5
				+	193	3.4	7.7
	pH 4.5	9.1	5.6	-	<6	<0.1	<0.1
II	Untreated	1.7	0.0	-	<2	<0.2	
				+	6	0.4	
	pH 6.0	3.8	1.5	-	<3	<0.1	<0.2
				+	21	0.6	1.4
	pH 4.5	7.0	4.6	-	<3	<0.1	<0.1
III	Untreated	7.3	0.0	+	10	0.1	-
				+	107	1.4	3.7
	pH 4.5	8.4	5.2	+	132	1.6	2.5
	CAN	7.2	3.6	+	90	1.2	2.5
	pH 4.5 on sand only	8.4	5.2	+	9	0.1	0.2

N₂O fluxes: experiment III

In experiment III, N_2O fluxes increased in the order: untreated slurry, CAN, treated slurries (Fig. 5A and Table 2). The low but significant slurry-derived flux from the NO_3^- free untreated slurry suggests that N_2O was released from nitrification of NH_4^+ , possibly in combination with subsequent denitrification.

The flux from treated slurries immediately after application, probably originated from the N_2O pool in the slurries. No flux could be detected immediately after application of CAN. The highest slurry- and CAN-derived fluxes occurred during the second day. After this peak, fluxes decreased gradually with time and 17 days after application fluxes from fertilized columns were similar to those from unfertilized columns. There was no clear diurnal pattern in fluxes related to changes in soil temperature (Fig. 5A and B) as found by Blackmer et al. (1982) and Denmead et al. (1979). Possibly, the effect of temperature variations was masked by the effect of regular irrigation.

Fluxes from slurry of pH 4.5 were equal to or only slightly higher than those from

NITROUS OXIDE FLUX FROM NITRIC-ACID-TREATED CATTLE SLURRY

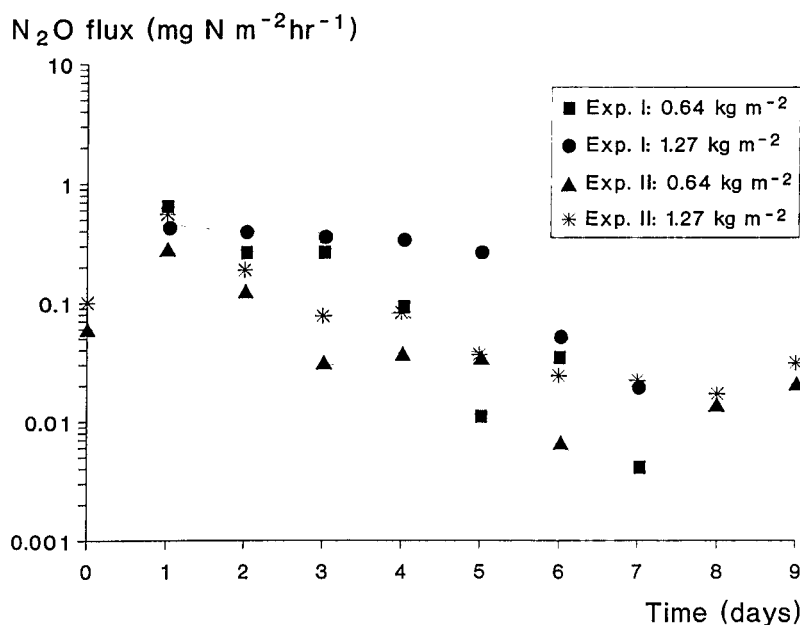


Fig. 4. Slurry-derived N₂O fluxes from treated cattle slurry of pH 4.5 surface-applied to a grass sward. Slurry was applied at rates of 0.64 and 1.27 kg m⁻². All treatments were irrigated daily. Means of four replicates, from experiments I and II. Note logarithmic scale of Y axis.

the slurry of pH 6.0. This corresponds with the results of experiment II and indicates that there was not an immediate effect of pH on N₂O flux, provided that slurry of pH 6.0 was treated immediately before application.

Surprisingly, fluxes from CAN were on average only slightly lower than those from treated slurries. This suggests that the sandy soil contained sufficient amounts of readily available carbon and sites of anaerobiosis for denitrification and N₂O production. With treated slurry both NO₃ and available carbon are applied. Application of slurry may also seal the soil, thereby creating anaerobic microsites in the soil with high denitrification activity, due to decreased O₂ diffusion and increased O₂ consumption (Beauchamp et al., 1989). The relatively small differences between CAN and treated slurries indicates that application of NO₃ was the most critical factor and that the soil was the dominant site of N₂O production.

The flux pattern of the treatment with pH-4.5 slurry applied to quartzitic sand is shown in Fig. 6. The flux from quartzitic sand was assumed to be negligible. During the first days no significant amounts of N₂O were emitted, except immediately after slurry application. A small but significant flux was measured from day 5 onwards. Apparently, it took some time for N₂O production to start in the sand-slurry environment. However, the fluxes were much lower from the quartzitic sand than from the sandy soil with sward. There are several possible explanations for these low fluxes, like the absence of soil organic matter, roots and a well-established denitrifying bacteria population in the quartzitic sand. Albeit unclear, the results of this treatment

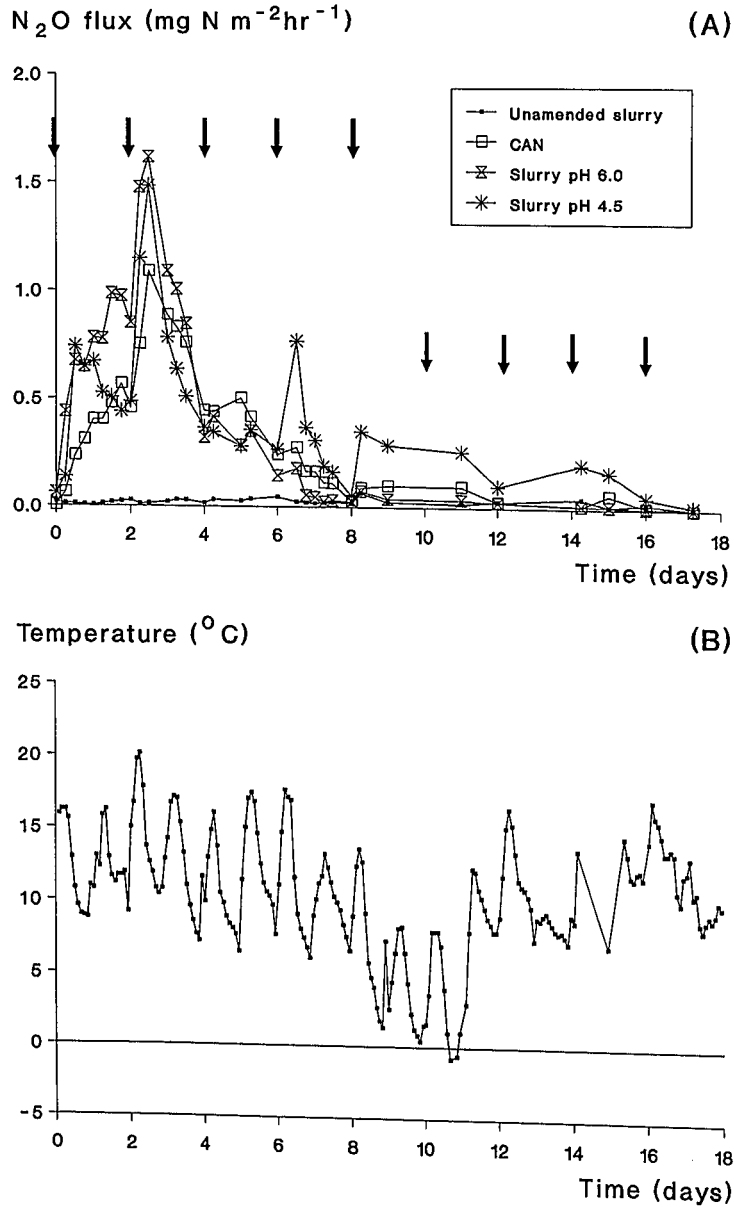


Fig. 5. (A) Slurry-derived N₂O flux from untreated slurry, treated slurries of pH 6.0 and pH 4.5 and fertilized-derived flux from CAN, surface-applied to a grass sward. Arrows indicate time of irrigation. Means of four replicates, from experiment III. (B) Course of the air temperature during experiment III.

confirm the suggestion that HNO₃ treated slurry itself was not the dominant site of N₂O production.

NITROUS OXIDE FLUX FROM NITRIC-ACID-TREATED CATTLE SLURRY

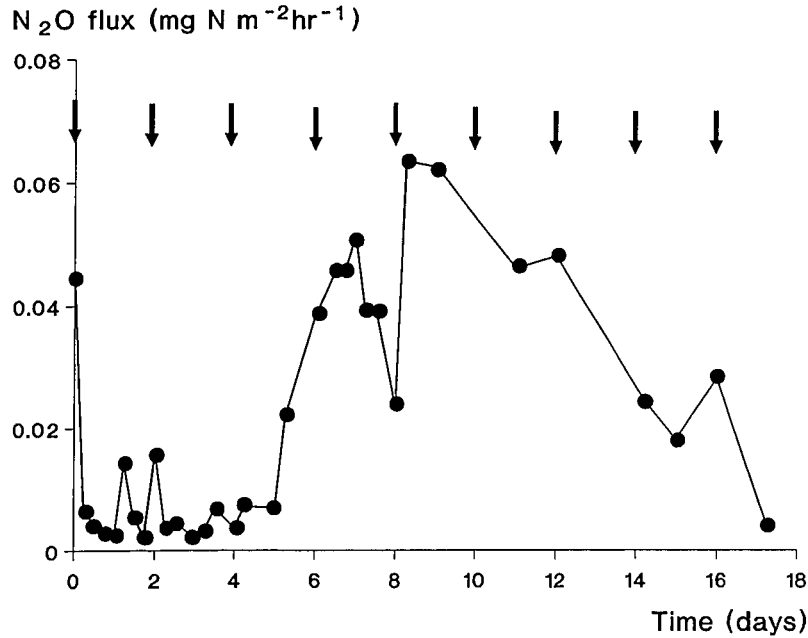


Fig. 6. Flux of N₂O from slurry of pH 4.5 surface-applied to quartzitic sand without a grass sward. Means of four replicates, from experiment III.

Summed N₂O losses

The summed slurry-derived N₂O losses were estimated by integrating the N₂O flux over time. Summed losses were lower in experiment II than in experiments I and III (Table 2). Part of this difference may be attributed to differences in slurry composition and in the duration of the measurement periods. Differences in weather conditions and temperature may also have contributed (Table 3). During the warm and sunny weather conditions of experiment II, grass growth and N uptake was faster than during the colder and cloudy weather conditions of experiments I and III. Obviously, the faster N is absorbed by a crop, the smaller the risk of denitrification and N₂O production. The overall effect of temperature on N₂O flux is difficult to predict.

Table 3. Mean, minimum and maximum temperatures during experiments I, II and III.

Expt	Temperature (°C)		
	mean	minimum	maximum
I. 10/6-17/6	13.4	7.2	20.2
II. 21/8-30/8	19.3	12.3	31.4
III. 30/9-17/10	10.3	-0.8	20.1

The denitrification rate increases with increasing temperatures, but the ratio between N_2O and N_2 produced during denitrification generally decreases (e.g. Keeney et al., 1979).

When irrigated, N_2O fluxes ($mg\ N\ m^{-2}\ hr^{-1}$) and summed N_2O losses (in % of N applied) were relatively high, but both are in the range of data reported in the literature (Eichner, 1990; Bouwman, 1990). Under non-irrigated conditions, losses were low. From an agricultural point of view, the total N_2O -N losses were relatively small; less than 3.4% of mineral N applied was emitted as N_2O (Table 2). However, the proportion of N_2O in the total N loss through denitrification may range from less than 5 up to more than 50 % (Ryden & Rolston, 1983). Hence, N_2O -N losses are a lower estimate of total N losses. The wide range indicates that it is impossible to deduce accurately total N losses from N_2O production data only.

Conclusions

The major conclusions from these experiments are:

- Coefficients of variation of average N_2O fluxes were relatively independent of slurry type and flux and, under the semi-controlled conditions of our experiments, as high as those reported for field conditions.
- HNO_3 treated cattle slurry emitted much more N_2O than untreated slurry; the amounts emitted by CAN were similar to those of treated cattle slurry.
- Irrigation markedly increased N_2O fluxes from HNO_3 treated slurries and CAN.
- N_2O fluxes were highest during the first three days after application; subsequently decreased to rates equal to that of the unfertilized treatments within 5-14 days.
- Slurry pH had no clear effect on N_2O flux if the slurry was treated one hour before application; if treated one week before application, fluxes were much higher from pH-6.0 slurry than from pH-4.5 slurry.

Acknowledgements

The authors thank Richard Oomkens for his technical assistance. This investigation was supported financially by 'Financierings Overleg Mest- en Ammoniakonderzoek' (FOMA).

References

- Beauchamp, E.G., J.T. Trevors & J.W. Paul, 1989. Carbon sources for bacterial denitrification. In: B.A. Stewart (Ed.), *Advances in Soil Science* 10, p. 113-142. Springer-Verlag, New York.
- Blackmer, A.M., S.G. Robbins & J.M. Bremner, 1982. Diurnal variability in rate of emission of nitrous oxide from soils. *Soil Science Society of America Journal* 46: 937-942.
- Bouwman, A.F. (Ed.), 1990. *Soils and the greenhouse effect*. John Wiley & Sons, Chichester, 575 pp.
- Bussink, D.W. & M.A. Bruins, 1992. Reduction in ammonia volatilization using different slurry application techniques on grassland. (In Dutch). *Meststoffen*: 31-36.
- Denmead, O.T., J.R. Freney & J.R. Simpson, 1979. Studies of nitrous oxide emission from a grass sward. *Soil Science Society of America Journal* 43: 726-728.
- Eichner, M.J., 1990. Nitrous oxide emissions from fertilized soils: summary of available data. *Journal of Environmental Quality* 19: 272-280.

NITROUS OXIDE FLUX FROM NITRIC-ACID-TREATED CATTLE SLURRY

- Firestone, M.K. & E.A. Davidson, 1989. Microbiological basis of NO and N₂O production and consumption in soil. In: M.O. Andreae & D.S. Schimel (Eds), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, Life Sciences Research Report 47, p. 7-21. John Wiley & Sons, Chichester.
- Frost, J.P., R.J. Stevens & R.J. Laughlin, 1990. Effect of separation and acidification of cattle slurry on ammonia volatilization and on the efficiency of slurry nitrogen for herbage production. *Journal of Agricultural Science (Cambridge)* 115: 49-56.
- Keeney D.R., I.R. Fillery & G.P. Marx, 1979. Effect of temperature on the gaseous nitrogen products of denitrification in a silt loam soil. *Soil Science Society of America Journal* 43: 1124-1128.
- Mosier, A.R., 1989. Chamber and isotope techniques. In: M.O. Andreae & D.S. Schimel (Eds), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere, Life Sciences Research Report 47, p. 175-187. John Wiley & Sons, Chichester.
- Oenema, O. & G.L. Velthof, 1993. Denitrification in nitric acid treated cattle slurry during storage. *Netherlands Journal of Agricultural Science* 41: 63-80.
- Oenema, O., G.L. Velthof & D.W. Bussink (1993). Emissions of ammonia, nitrous oxide and methane from cattle slurry. In: R.S. Oremland (Ed.). *The Biogeochemistry of Global Change: Radiative Trace Gases*, p. 419-433. Chapman and Hall, New York.
- Pain, B.F., R.B. Thompson, Y.J. Rees & J.H. Skinner, 1990. Reducing gaseous losses of nitrogen from cattle slurry applied to grassland by the use of additives. *Journal of the Science of Food and Agriculture* 50: 141-153.
- Ryden, J.C. & D.E. Rolston, 1983. The measurement of denitrification. In: J.R. Freney and J.R. Simpson (Eds). *Gaseous loss of nitrogen from plant-soil systems. Developments in Plant and Soil Sciences*, Vol. 3, p. 91-132. Martinus Nijhoff, Dordrecht.
- Stevens, R.J., R.J. Laughlin & J.P. Frost, 1989. Effect of acidification with sulphuric acid on the volatilization of ammonia from cow and pig slurries. *Journal of Agricultural Science (Cambridge)* 113: 389-395.
- Stevens, R.J., R.J. Laughlin, J.P. Frost & R. Anderson (1992). Evaluation of separation plus acidification with nitric acid and separation plus dilution to make cattle slurry a balanced, efficient fertilizer for grass and silage. *Journal of Agricultural Science (Cambridge)*: 119: 391-399.