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REGULAR ARTICLE

Nitrous oxide emissions from multiple combined applications of fertiliser and cattle slurry to grassland

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Abstract Fertiliser and manure application are important sources of nitrous oxide (N_2O) emissions from agricultural soils. The current default IPCC emission factor of 1.0% is independent of the type of fertiliser and manure, and application time, method and rate. However, in the IPCC Tiered system it is possible to use more specific emission factors that better reflect the actual fertiliser and manure management in a given country or region. The first and primary aim of this study was to determine whether the combination of cattle slurry injection with fertiliser application, which is common practice in intensively managed grasslands in the Netherlands and neighbouring countries, warrants an adjusted emission factor. A second aim was to evaluate whether alternative emission factors, based on N uptake and N surplus, respectively, give more insight in the N_2O emission rates of various fertilisation strategies. In a 2-year field experiment on sandy soil in the Netherlands we measured the annual N_2O emission from grasslands receiving repeated simultaneous applications of fertiliser and cattle slurry. The N_2O fluxes and N uptake by grass were measured from plots receiving calcium ammonium nitrate (CAN) at four application rates, either with or without additional application of liquid cattle slurry, applied through shallow soil injection. The average emission factor for fertiliser-only treatments was 0.15%. The annual N_2O emissions were similar for treatments receiving only fertiliser or only cattle slurry. In the first experimental year, application of cattle slurry increased the emission factor for fertiliser to 0.35%, but the second year showed no effect of cattle slurry on the emission from fertiliser. With regard to the first objective, we conclude that these results do not conclusively justify an adjusted emission factor for combined application of fertiliser and cattle slurry. To minimise risks however, it is sensible to avoid simultaneous application of fertiliser and cattle slurry. The N_2O emission factor expressed as percentage of kg N uptake by grass was consistently higher after combined application of fertiliser and cattle slurry (0.29%), compared to fertiliser-only (0.17%). With regard to the second objective we conclude that an emission factor based on N uptake expresses the relatively inefficient N supply of cattle slurry to crop growth better than the traditional emission factor based on N application.

Keywords Cattle slurry · Emission factor · Fertiliser · Grassland · Manure · Nitrous oxide

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Introduction

Soil applied fertiliser and animal wastes are the two most important sources of direct nitrous oxide (N_2O) emissions from agricultural soils (Mosier et al. 1998). In the European Union (EU-15), 40% of the direct soil emission is attributed to fertiliser application, and another 21% to manure application (EEA 2006). In the year 2000, grasslands in the EU-15 received approximately 24% of the total amount of applied fertiliser N, and 32% of the applied manure N (Velthof et al. 2007). The default IPCC emission factor, i.e. the percentage of applied N emitted as N_2O, is 1.00%, irrespective of the type of fertiliser or manure (IPCC 2006). Also application time, application method and application level are not considered. The default emission factor is based on an average of published measurements on a wide range of soil types, crops, fertiliser types, N sources, N levels and application times and methods (Bouwman 1996; Bouwman et al. 2002; Stehfest and Bouwman 2006). Individual countries can use a different emission factor that corresponds to country-specific soil types or farm management. The data used to derive the IPCC default emission factor originate predominantly from fertiliser experiments. For grassland, the dataset contains relatively few experiments with organic N sources or combinations of fertiliser and organic N. This is in contrast with the farming practice of intensively managed grasslands in Europe, where both fertiliser and cattle slurry are usually applied shortly after one another. In those cases, interactions between those different N sources should be considered. Therefore, following the Tiered system for country-specific emission factors, it is useful to measure N_2O emissions of fertiliser N in combination with applied cattle slurry. In recent years, some experiments were carried out with combined application of fertiliser and cattle slurry to grassland (Clayton et al. 1997; Dittert et al. 2005; Stevens and Laughlin 2001, 2002). All experiments reported higher N_2O emissions when fertiliser and cattle slurry where applied simultaneously than when they were applied separately or with a larger interval in-between. These higher N_2O losses were attributed to enhanced denitrification through the simultaneous availability of fertiliser derived nitrate (NO_3) and cattle slurry derived easy degradable carbon (C). However, in these experiments cattle slurry was surface-applied. Efforts in recent years to reduce ammonia losses have led to an increased use of animal slurry injection techniques, especially in the Netherlands. Studies that compared application techniques of cattle slurry have either shown no effect of application technique (e.g. Velthof et al. 1996) or a higher N_2O emission following cattle slurry injection (e.g. Rodhe et al. 2006). However, these experiments had no treatments with combined fertiliser and cattle slurry application and therefore did not consider possible interactions. To our knowledge, there are no published N_2O emission measurements following a combined application of fertiliser and injected cattle slurry on grassland.

Intensively managed grasslands in North-West Europe are usually fertilised four to seven times a year, combined with two to four cattle slurry applications (Unwin and Vellinga 1994; Schröder et al. 2007). Therefore, the current practice might require a specific emission factor, other than the IPCC default. The primary objective of this paper was to assess the annual N_2O emission from intensively managed grasslands fertilised according to common agricultural practice in the Netherlands, i.e. with repeated simultaneous applications of fertiliser and injected cattle slurry. More specific, we aim to determine the effect of cattle slurry application on the N_2O emission from fertiliser.

The IPCC emission factors imply a linear relationship between N input and N_2O emissions. The principal advantage of this approach is that the activity data, at least for fertiliser use, are relatively easy to collect and use in national inventory systems. A drawback is that the fixed emission factors only stimulate mitigation through reduced inputs and are not an incentive to improve the N use efficiency by crops. Experiments with different application rates have shown increased emission factors with increasing application rates (Ryden 1983), but others have found contrasting results (Velthof et al. 1996), that were attributed to the differences between sites in soil inorganic N accumulation. The use of process-orientated simulation models, e.g. DNDC (Li et al. 1992), may to some extent clarify these uncertainties, but the scope for general application of such models is limited. Emission factors based on either N uptake by crops or N surplus, i.e. the difference between N input through fertilisers and manure and the N output through crop uptake, may provide attractive alternatives. An emission factor based on crop N uptake might be a better expression of the effectiveness of a cropping system in producing biomass while minimizing greenhouse gas emissions. An emission factor based on the N surplus may be a more realistic candidate for a linear emission factor, as it corrects for N uptake efficiency. Therefore the second objective of this paper was to compare the emission factors for N input with emission factors linked to N uptake and N surplus.

To address these objectives, we carried out a 2-year experiment in which N uptake and N_2O emission was measured from multiple applications of fertiliser and cattle slurry, separately or combined, and at different fertiliser application rates. The experiment was carried out on a sandy soil as the farms on those soils are among the most intensive farms in Europe, with high applications of cattle slurry and fertiliser. Application of cattle slurry through injection techniques are mostly applied on these lighter soil types.

Materials and methods

Location

The experiment was carried out at the Droevendaal experimental farm in Wageningen, the Netherlands (51°59′ N, 5°39′ E). The soil is an umbric gleysoil (FAO 1998) with 3.5% organic matter and a pH_{KCl} of 5.5 in the top soil (0–5 cm). The experimental field was located on a larger field that was ploughed and reseeded in the autumn of 1999 with a 100% perennial ryegrass (*Lolium perenne* L.) seed mixture. In the previous years, the area was used for alternate cutting and grazing with an average fertiliser application of 200 to 300 kg N ha^{-1} $year^{-1}$ and additional cattle slurry application of 20 to 40 t ha^{-1} $year^{-1}$.

Experimental setup

The core of the experiment consisted of a comparison of treatments receiving either fertiliser alone with treatments receiving fertiliser and cattle slurry. The fertiliser used was calcium ammonium nitrate (CAN, 13.5% $NH_3{-}N$ and 13.5% $NO_3{-}N$), which is the most commonly used fertiliser type in the Netherlands. The cattle slurry was liquid slurry with an average total N content of 4.17 and 4.93 g kg^{-1} in the first and second year, respectively. The proportion of $NH_4{-}N$ was 47% in the first year and 50% in the second year. Fertiliser was broadcast by hand. The cattle slurry was applied, according to common practice on mineral soils in the Netherlands, with a shallow injection technique, applying the cattle slurry in open equidistant slits (20 cm), approximately 2 cm wide and with a depth of 10 cm.

Both the fertiliser-only and fertiliser-slurry treatments were carried out at four fertiliser application levels (Table 1). The resulting eight treatments were laid out in a randomised block design with three replicates. Plots were 10 m by 2.8 m. The N application levels on the fertiliser-only treatments CAN_0, CAN_50, CAN_75 and CAN_100 were 0, 160, 240 and 320 kg ha^{-1} $year^{-1}$, respectively. The distribution of the annual fertiliser application over the five cuts was 35, 20, 15, 15 and 15%, respectively. The treatments with combined fertiliser and cattle slurry application, received 90 t ha^{-1} $year^{-1}$ of cattle slurry, supplemented with either 0, 120, 180 or 240 kg N ha^{-1} $year^{-1}$ from fertiliser for treatments CS_0, CS_50, CS_75 and CS_100, respectively. Cattle slurry was applied at a rate of 30 t ha^{-1} for the first and second cut, and 15 t ha^{-1} for the third and fourth cut. The distribution of the annual fertiliser application was adapted to match the fertilising value of the applied cattle slurry, and was 30, 20, 15, 15 and 20% for the five consecutive cuts, respectively. On the fertiliser-slurry treatments, fertiliser and cattle slurry were applied on the same day.

The experiment was carried out in the year 2001 and 2002, both years on the same plots.

Grass and soil analysis

All plots were harvested five times, between May and October of each year, with a Haldrup plot harvester at a cutting height of 5 cm. Fresh grass yields were determined and samples were taken for analysis on dry matter (DM) and total N. The DM content was determined after 48 h drying at 70°C. Dried samples were milled and total N content was determined spectrophotometrically after destruction with H_2SO_4 using standard methodology in a mixture with salicylic acid and Se, to which H_2O_2 was added.

The DM yield and N uptake was calculated from the fresh yields, DM contents and N contents. The apparent N recovery (ANR) of fertiliser and cattle slurry in harvested grass was calculated from the N

Table 1 Annual nitrogen application rates from fertiliser and cattle slurry, dry matter and nitrogen uptakes, nitrous oxide emissions and emission factors

Treatment	Fertiliser (kg N ha^{-1})	Cattle slurry (kg N ha^{-1})	DM yield (kg ha^{-1})	N uptake (kg ha^{-1})	N_2O[a] (kg N ha^{-1})	EF_applied[b] (%)	EF_applied[c] (%)	EF_uptake (%)	EF_surplus (%)
2001									
CAN_0	0	0	3,195	65	0.04 (0.07)			0.07	−0.07
CAN_50	120	0	7,048	175	0.17 (0.18)	0.11		0.10	−0.31
CAN_75	240	0	9,356	263	0.60 (0.67)	0.23		0.23	−2.59
CAN_100	330	0	10,240	314	0.60 (0.56)	0.17		0.19	3.86
CS_0	0	375	8,116	196	0.46 (0.52)	0.11		0.24	0.26
CS_50	120	375	11,123	295	0.87 (0.93)	0.17	0.34	0.30	0.43
CS_75	180	375	11,415	325	1.02 (1.04)	0.18	0.31	0.31	0.44
CS_100	240	375	12,250	367	1.41 (1.45)	0.22	0.40	0.38	0.57
Sign./LSD ($P<0.05$)[d]									
N source			***(311)	***(10.3)	***(0.17)			**(0.059)	NS
N level			***(439)	***(14.5)	***(0.24)			*(0.083)	***(1.9)
N source *N level			***(621)	***(20.5)	NS			NS	***(2.7)
2002									
CAN_0	0		3,703	72	0.13			0.18	−0.18
CAN_50	120		6,613	150	0.30	0.14		0.20	−0.99
CAN_75	240		7,308	208	0.41	0.12		0.20	1.28
CAN_100	330		7,962	275	0.53	0.12		0.19	0.97
CS_0	0	444	10,098	215	0.66	0.12		0.31	0.29
CS_50	120	444	10,956	291	0.69	0.10	0.02	0.24	0.25
CS_75	180	444	10,385	305	0.73	0.10	0.04	0.24	0.23
CS_100	240	444	10,912	365	1.14	0.15	0.20	0.31	0.36
Sign./LSD ($P<0.05$)[d]									
N source			***(619)	***(23.5)	***(0.13)			*(0.060)	NS
N level			***(875)	***(33.2)	***(0.18)			NS	NS
N source *N level			**(1,237)	NS	NS			NS	NS

[a] Between brackets full year N_2O emission until March 2002, thus including emissions outside the growing season, for better comparison with IPCC default value

[b] Emission factor as percentage of total applied N, relative to CAN_0

[c] Emission factor as percentage of applied fertiliser N, relative to CS_0

[d] Signicance levels: ***$P<0.001$, **$P<0.01$, *$P<0.05$. *LSD*, Least significant difference at $P<0.05$

uptake of plots receiving only fertiliser ($NU_{fertiliser}$) or only cattle slurry (NU_{slurry}), the N uptake of the unfertilised control ($NU_{control}$), and the applied N ($N_{applied}$) as follows:

$$\mathrm{ANR}_{\mathrm{fertiliser/slurry}}(\%) = \left(\mathrm{NU}_{\mathrm{fertiliser/slurry}} - \mathrm{NU}_{\mathrm{control}}\right) * 100/\mathrm{N}_{\mathrm{applied}}$$

Following each harvest, but before the next fertiliser or cattle slurry application, soil samples were taken to a depth of 20 cm. The samples were extracted with 1 M KCl, after which NH_4^+ and NO_3^- concentrations were determined spectrophotometrically. The total amount of NH_4^+–N and NO_3^-–N in the layer of 0–20 cm was calculated, using a bulk density of 1.41 g cm^{-3}, determined in 2002 on the same field.

Subsequently, the soil samples were dried for 24 h at 105°C to determine gravimetric soil moisture content. The gravimetric soil moisture contents were recalculated to water filled pore space (WFPS), using the bulk density of 1.41 g cm^{-3}, and assuming densities of 1.47 and 2.65 g cm^{-3} for the organic and mineral soil fractions, respectively. At each flux measurement, soil temperature was measured at a depth of 10 cm using Pico PT-100 temperature probes.

Daily rainfall and average temperature were collected from a weather station at a distance of 1 km of the experimental field.

Nitrous oxide measurements

Nitrous oxide fluxes were measured on 57 occasions between 3 April 2001 and 7 October 2002. The measuring frequency was up to three times a week after fertiliser and cattle slurry application and two to four times a month in the remainder of the growing season. An additional set of four measurements was carried out between the end of the first growing season and the start of the second growing season. To prevent effects of diurnal variation, all emission measurements were carried out between 9 and 12 AM. Although this ensures a good comparison between the daily flux measurements, the annual emission levels may have been underestimated. Earlier studies showed that diurnal N_2O production varies with diurnal soil temperature, which is at its lows at sunrise (Christensen 1983; Williams et al. 1999) and peaks late afternoon.

The N_2O concentrations were measured in the headspace of vented closed PVC flux chambers, with a diameter of 16 cm and a height of 15 cm, using a Brüel and Kjær photo-acoustic spectroscopic infrared gas analyser (Velthof and Oenema 1995a). The flux chambers were placed onto semi-permanent rings, inserted into the soil to a depth of 2 cm. The rings remained in the soil during each harvest cycle, and were moved to new positions after each fertiliser and cattle slurry application. The placement of the rings on the plots receiving cattle slurry received special attention in order to achieve the correct proportion between applied and non-applied surface within the flux chambers. Therefore the centre of the rings was placed at a distance of 6 cm from the application slit.

The N_2O concentration was measured before the chambers were closed and approximately 45 to 60 min after closing. The analyser was attached directly to the flux chambers by two Teflon tubes. A soda lime trap was installed at the inlet of the analyser to prevent undesired accumulation of carbon dioxide (CO_2). The analyser was fitted with optical filters for selective measurement of N_2O, CO_2 and water vapour. Any remaining CO_2 was automatically corrected for. The accuracy of the analyser was approximately 5% in the range of 300 to 5,000 ppb.

The N_2O flux was calculated as the difference between ambient concentration and the concentration in the closed chamber, assuming a linear relationship between concentration and time (Velthof and Oenema 1995a), which was occasionally checked during the experiment. The accumulated fluxes were calculated by linear interpolation between measurement days. Emission factors were calculated in three ways. In the conventional method the emission factor ($EF_{applied}$) is calculated from the N_2O emission of fertilised and/or manured plots (N_2O_{fert}), the N_2O emission of control plots (N_2O_{zero}) and the amount of total N applied, all expressed in kg N ha^{-1}:

$$EF_{applied}[\%] = (N_2O_{fert} - N_2O_{zero}) * 100/\text{N applied}$$

Alternatively, the emission (N_2O) was related to the N uptake of grass (EF_{uptake}), all expressed in kg N ha^{-1}, which could be calculated for each individual plot:

$$EF_{uptake}[\%] = N_2O * 100/\text{N uptake}$$

Finally, the emission was related to the N surplus ($EF_{surplus}$), defined as the difference between N uptake of grass and the total N input (kg N ha^{-1}) through fertiliser and cattle slurry:

$$EF_{surplus}[\%] = N_2O * 100/\text{N surplus}$$

Data analysis

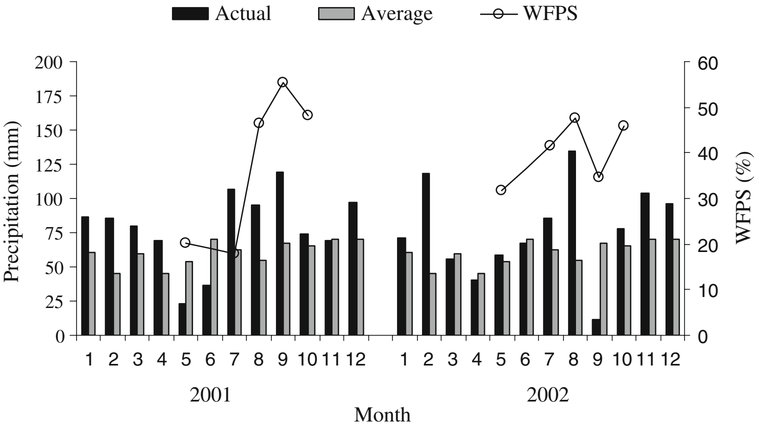
A two-way analysis of variance was performed to test the effects of the main treatments, the N application level, and their interactions. Multiple linear regression was used to relate N_2O emission with N application, N uptake or N surplus, and their interactions with the two N sources CAN and CS. The statistical analysis were carried out with GENSTAT (GENSTAT 2007).

Results

Soil

Both experimental years were relatively wet and warm, compared to the 30-year averages (1970–1999) of 724 mm year^{-1} and 9.5°C. The annual precipitation was 943 and 921 mm in 2001 and 2002, respectively. In 2001, the most of the excess precip-

Fig. 1 Monthly actual and 30 year average precipitation (*left axis*), and water filled pore space (WFPS, 0–20 cm) at harvest (*right axis*)



itation occurred between January and April and between August and October (Fig. 1). May and June of 2001 were relatively dry months. In 2002, February and August were extremely wet, while September was the driest month by far. The WFPS (Fig. 1) varied from 18% in May and June 2001 to around 50% at the end of the first growing season. In 2002, the WFPS values were in a smaller range in than in 2001. Due to the large measurement interval, it can not be excluded that the actual WFPS values were outside the described range.

The average annual temperatures were 10.3 and 10.7°C in 2001 and 2002, respectively (Fig. 2). All monthly temperatures were higher than average, but the differences were more prominent outside than during the growing season. Soil temperatures followed the pattern of air temperature and ranged from 7 to 27°C.

The total amount of soil inorganic N in the top soil (0–20 cm) at harvest varied from less than 5 kg N ha^{-1} to incidentally nearly 50 kg N ha^{-1} on plots receiving the highest amounts of fertiliser and cattle slurry (Fig. 3). In the first year, significant accumulation of NH_4^+-N only occurred at the second harvest, with on average a higher accumulation on fertiliser-only plots. At the first harvest in 2002, soil NH_4^+-N was significantly ($P<0.01$) higher on the manured plots, but without any effect of N level. The fourth harvest in 2002 also showed significant NH_4^+–N accumulation, with generally higher amounts on the manured plots. Differences in accumulation of NO_3^-–N occurred at nearly all harvests. Nitrate accumulation was higher on the manured plots at all harvests in the first year, and at the first, fourth and fifth harvest of the second year. Application level had a positive effect on soil NO_3^-–N at the second and third harvest in the first year, and at all harvests in the second year. The occurrence of dry periods in May and June 2001 coincided with the most noticeable accumulation in July 2001. Similarly, the accumulation in September 2002 was preceded by a dry period in the month before.

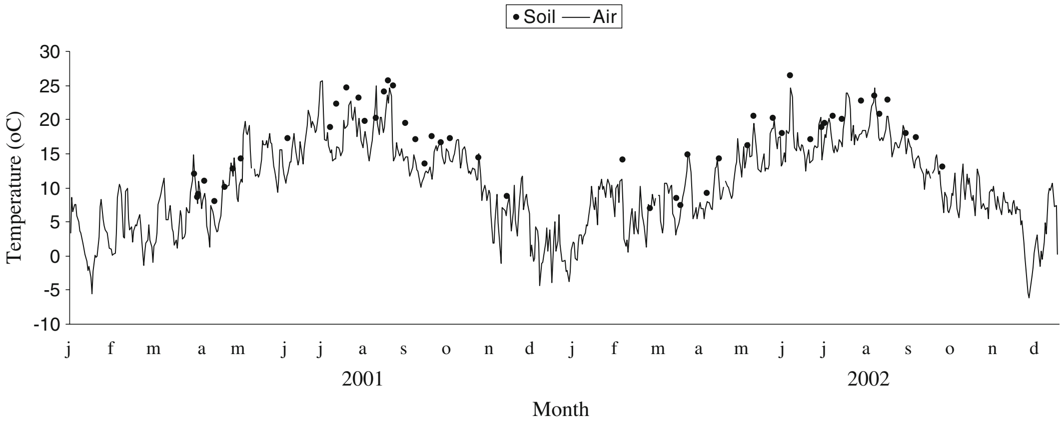


Fig. 2 Mean daily air temperature at 150 cm and soil temperature on N_2O flux measurement dates at a depth of 10 cm

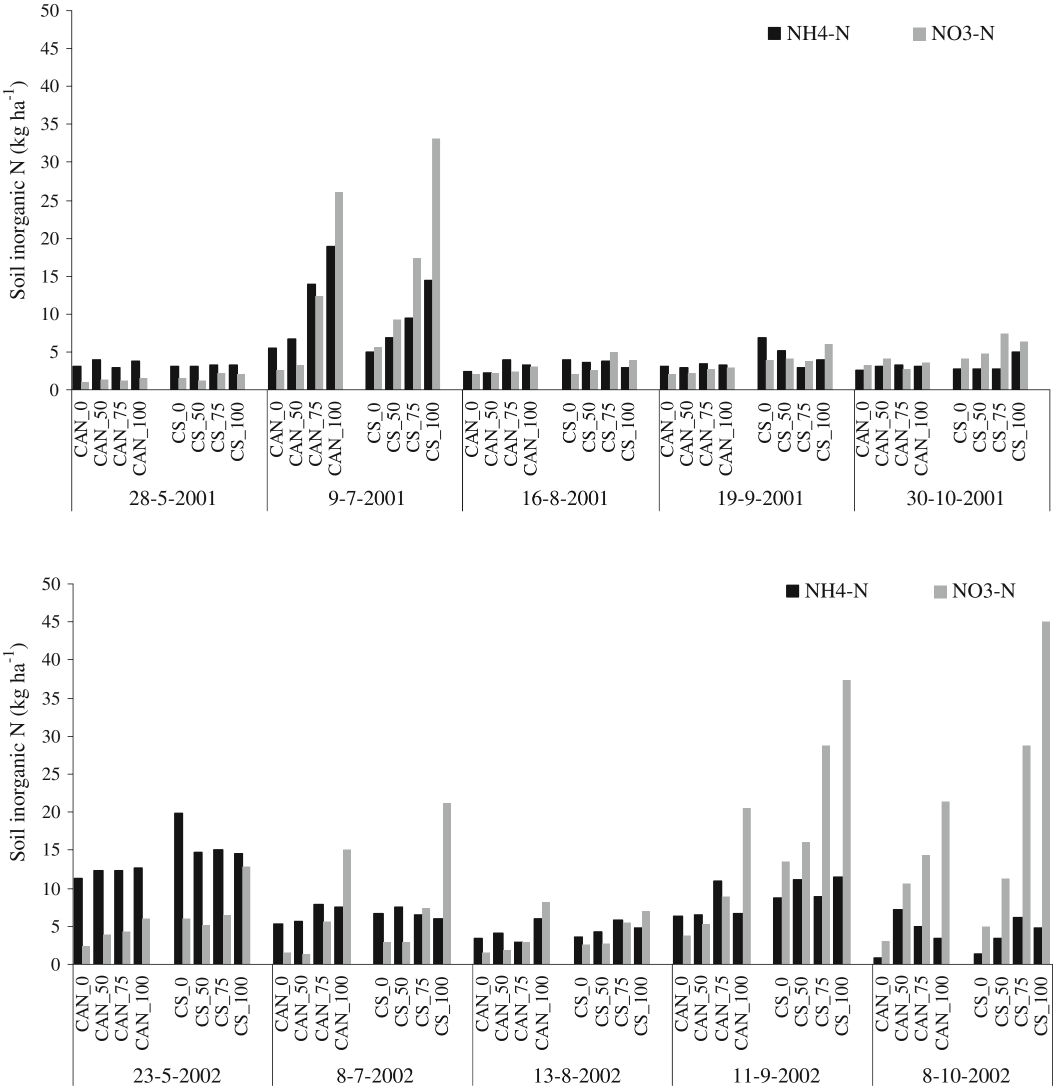


Fig. 3 Soil inorganic NH_4–N and NO_3–N to a depth of 20 cm, for all treatments at all individual harvests

Grass

The DM yield of the unfertilised control plots were 3.2 and 3.7 t ha^{-1} year^{-1} in the first and second year, respectively (Table 1), with corresponding annual N uptakes of 65 and 72 kg ha^{-1}. Application of fertiliser N significantly increased DM and N uptakes, with and without application of cattle slurry. In both years, the maximum N uptake was around 365 kg ha^{-1} year^{-1}. However, the DM production per unit N uptake was higher in the first than in the second year, with corresponding maximum DM yields of 12.3 and 10.9 t DM ha^{-1} year^{-1} for 2001 and 2002, respectively. The ANR of fertiliser-N ranged from 69 to 82% in the first year, and from 56 to 65% in the second year. The ANR of slurry-N was 35 and 30% in year 1 and two, respectively.

Nitrous oxide emissions

The N_2O fluxes varied from −1.6 g N_2O–N ha^{-1} d^{-1} on the unfertilised control plot (CAN_0) to 48 g N_2O–N ha^{-1} d^{-1} on the plot receiving the highest fertiliser application in combination with cattle slurry (CS_100) (Fig. 4). Generally, the highest N_2O fluxes occurred in the first week after fertiliser or cattle slurry application. No differences in the general emission pattern could be observed between fertiliser and cattle slurry treatments.

On three occasions, fertiliser and manure application was not followed by a distinct peak emission. For the second application in 2001 and the fifth application in 2002, the absence of a peak coincided with a longer period of drought. In the case of the first application in 2002 there was no evidence of dry soil conditions and the absence of the peak remains unclear

Emission peaks did not exclusively occur directly after application. For instance, the increased fluxes occurring on the 8th of August 2002, just a week before the fourth application, coincided with 14 mm rainfall 1 day earlier and 37 mm rainfall 3 days earlier.

Emissions outside the growing season, measured between October 2001 and March 2002. were only 4% of the annual emission (Table 1). Therefore, and for better comparability with the second year, we mainly present and analyse the accumulated emissions between March and October of each year.

On the control plots, the total N_2O emissions were 0.04 and 0.13 kg N ha^{-1} in the first and second year, respectively (Table 1). Application of fertiliser and cattle slurry increased the emissions up to levels of 1.41 kg N ha^{-1} in 2001 and 1.14 kg N ha^{-1} in 2002. In both years, N_2O emissions increased with fertiliser levels ($P<0.001$), irrespective of whether cattle slurry was applied or not. The average emissions were higher on the manured plots than on the fertiliser-only plots ($P<0.001$).

Emission factors

For the fertiliser-only treatments, the average emission factors, calculated as the percentage of applied N

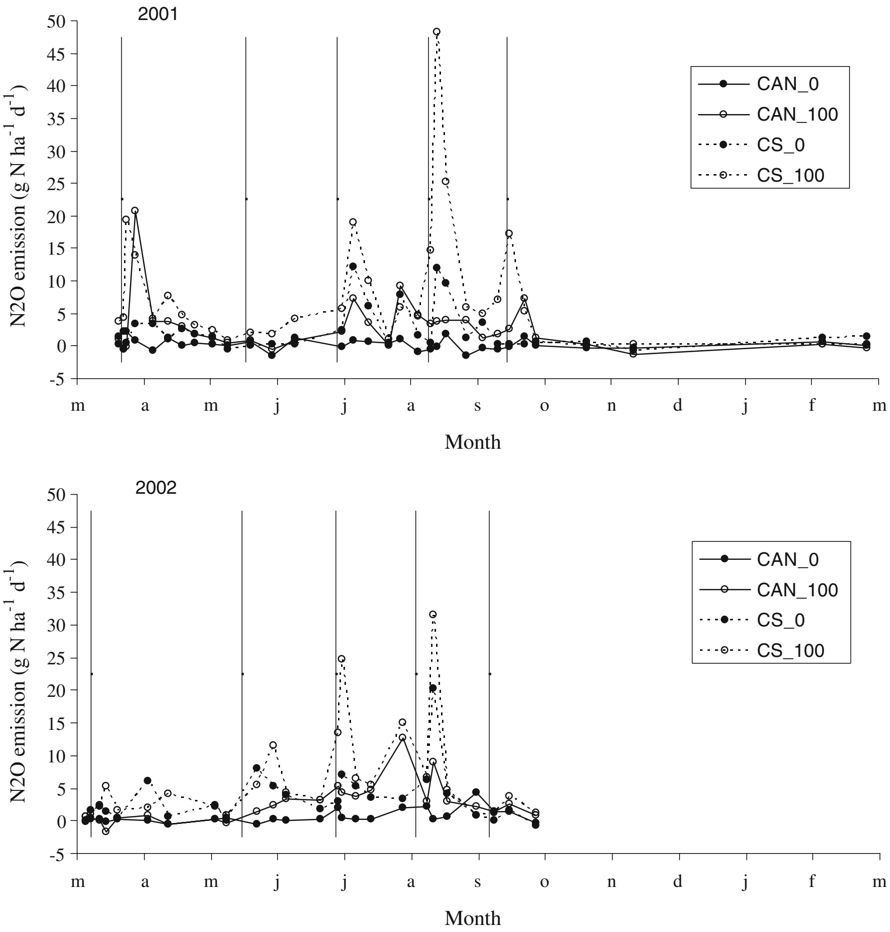


Fig. 4 Nitrous oxide emissions during the experiment of four selected treatments. *Vertical lines* represent the application date of fertiliser and cattle slurry

(EF_applied), were 0.17 and 0.13% in 2001 and 2002, respectively (Table 1). The inclusion of the measurements outside the growing season, between October 2001 and March 2002, did not affect the emission factor for that year. The emission factor of the slurry-only (CS_0) treatment was 0.11 and 0.12% in 2001 and 2002, respectively. The effect of cattle slurry application on the emission factor of fertiliser was not consistent. In the first year, the average emission factor of fertiliser was 0.35% on the CS-treatments, compared to 0.17% on the CAN-treatments. Regression analysis confirmed the higher emission factor for fertiliser ($P<0.05$) on the plots with cattle slurry application (Fig. 5). In the second year however, there was no effect of cattle slurry application on the emission factor for fertiliser. The average emission factor of fertiliser was 0.09% on the CS-treatments, compared to 0.13% on the CAN-treatments. Regression analysis showed no effects of N source on the N_2O emission in 2002.

The emission factor based on the N uptake of the grass crop (EF_uptake) varied from 0.07% on unfertilised plots (CAN_0) to 0.38% on plots receiving the highest combination of cattle slurry plus fertiliser (CS_100) (Table 1). In both years, the emission factors were significantly higher on treatments with cattle slurry application, viz. 0.29% compared to 0.17% for the fertiliser-only treatments. Regression analysis also showed the significantly higher N_2O emission per kg N uptake on the cattle slurry treatments (Fig. 5). In 2001, cattle slurry enhanced the emission of fertiliser N, which is similar to the effect observed with the conventional emission factor.

For the fertiliser-only treatments, the average N surplus varied from −72 to + 55 kg N ha^{-1} year^{-1}. The cattle slurry treatments had an average N surplus

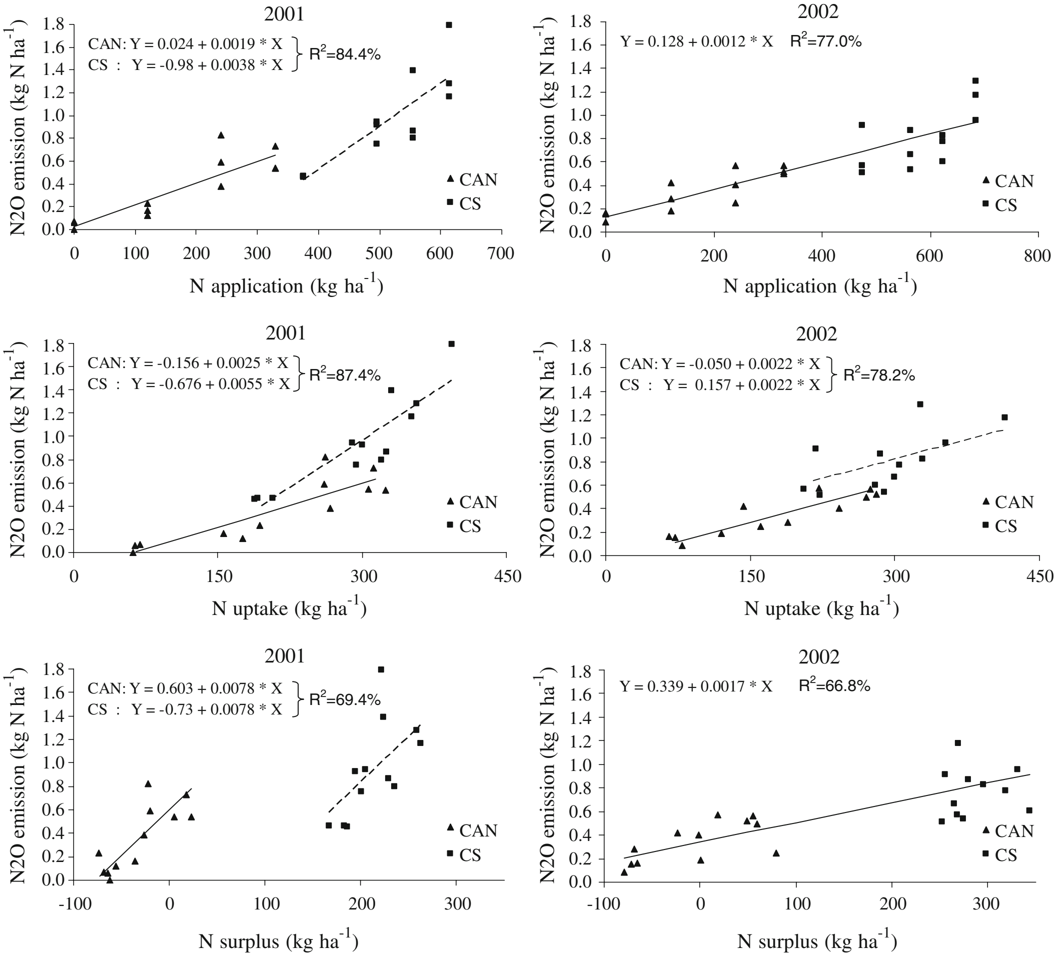


Fig. 5 Annual nitrous oxide emission in relation to applied N, N uptake and N surplus

between 179 to 319 kg N ha^{-1} year^{-1}. The emission factor, calculated as a percentage of the N surplus (EF_surplus) varied from −2.6 to 3.9% (Table 1). In 2001, N level had an effect ($P<0.001$) on the emission factor, but only within the fertilizer-only treatments.

Discussion and conclusions

Nitrogen efficiency

The average annual N uptake of the unfertilised control plots was 69 kg N ha^{-1} year^{-1}, which is in the low end of the range of 50 to 250 kg ha^{-1} which is typical for Dutch grasslands (Vellinga and Andre 1999). The low annual N uptake on unfertilised plots indicates a low soil N supply (Hassink 1995). The average ANR of applied fertiliser N was 82% in the first year and 61% in the second year. The lower ANR in the second year corresponds with the higher accumulation of soil inorganic N in that year. It may be hypothesised that in the second year a larger part of fertiliser N, not taken up by the grass, accumulated in the soil profile.

The average ANR of cattle slurry N was 33%, which is nearly half of the ANR of fertiliser. In terms of fertilising value, each kg of slurry N was equivalent to 0.46 kg of fertiliser N, which is within the usual range for this application technique (Schils and Kok 2003). The lower ANR of cattle slurry is partly caused by ammonia losses, which are typically around 5 to 10% of total N for the shallow injection technique (Huijsmans et al. 2001). Furthermore approximately 50% of the slurry N is of organic origin with a low ANR in the year of application. However, this also implies an additional supply of nitrogen to the soil, mainly of organic origin. The observed accumulation of soil NO_3^-−N on cattle slurry treatments indicates a fast turnover of NH_4^+−N originating from cattle slurry. Furthermore, the lower ANR of cattle slurry is clearly reflected in the higher N surpluses for the slurry treatments.

N_2O emission levels

The observed N_2O emission levels in this experiment were rather low compared to the IPCC default emission factor of 1.00%. The average emission factor for CAN fertiliser of 0.15% is in the lower end of the range, from 0.02 to 3.85%, reported in an overview of 31 experiments in the Netherlands (Kuikman et al. 2006). In an experiment on grassland, Velthof and Oenema (1995b) determined emission factors of 0.5, 1.4 and 3.1% for sand, clay and peat soils, respectively. The increasing emissions from sand to peat are usually attributed to increasing moisture contents in combination with increasing organic matter contents. We suspect that the low values of WFPS during our experiment is the driving factor for the low N_2O emissions, in line with findings in literature (Del Prado et al. 2006; van Groenigen et al. 2005), that suggest maximal N_2O losses at 70 to 80% WFPS. The sparse WFPS measurements in our experiment are not conclusive, but the observed range between 18 and 55% suggests poor conditions for N_2O production.

The emissions showed a temporal variation that was mainly driven by fertiliser and cattle slurry application events. Emission peaks generally occurred within the first week following application of fertiliser and cattle slurry. This is in agreement with other studies on intensively managed grasslands (Velthof and Oenema 1995b). Grasslands can rapidly absorb the applied N, and soil mineral N contents usually decrease rapidly within 2 weeks of application. Therefore the period of highest N_2O emission risk on grasslands are found within the first 2 weeks after application. The measurement frequency was fixed beforehand with a focus on frequent measurements during the first 2 weeks after application.

Effects of cattle slurry

The two experimental years gave contrasting results with regard to the effect of cattle slurry on the N_2O emission of fertiliser N. In the first year, the emission of fertiliser N was doubled in the presence of cattle slurry, but in the second year there was no significant effect. Reporting results from treatments with surface application of cattle slurry, Stevens and Laughlin (2001) found a threefold increase of the emission from KNO_3 fertiliser. In a short-term experiment, Dittert et al. (2005) also observed significant increases in the emission from CAN fertiliser when applied in combination with cattle slurry. The set-up of the experiment does not allow an in-depth analysis of the underlying mechanisms of N_2O production with or without cattle slurry application.

It might be hypothesized however that the contact area between applied fertilizer and injected cattle slurry is less than with surface applied cattle slurry. Therefore the risk of increased N_2O emissions from fertilizer might be lower with injection than with surface application.

If cattle slurry was applied alone, the emission factor was not different from fertiliser alone. By contrast, under very wet conditions, Velthof et al. (1996) measured a much higher emission from CAN fertiliser than from cattle slurry.

We hypothesized that the supply of easily degradable slurry C would increase the N_2O losses from fertiliser derived NO_3. The findings in the first year confirmed our hypothesis. It is unclear why the second year showed no effect of cattle slurry on N_2O emissions from fertiliser. The second year showed a higher accumulation of soil inorganic N. Under those circumstances, the additional supply of slurry derived C will not increase N_2O production. Furthermore, the differences in N_2O emissions between both years may have been caused by differences in the ratio between N_2O and N_2 production during denitrification (Firestone et al. 1980; Granli and Bøckman 1994). The choice for a location on dry sandy soil might have contributed to the lack of a consistent interaction between fertiliser and cattle slurry. Nevertheless, the risk of increased emissions following simultaneous fertiliser and cattle slurry application remains, as demonstrated clearly by the results in the first year.

Emission factors

The three differently derived emission factors used in this paper allow alternative interpretations of the results. The emission per kg N uptake (EF_uptake) was consistently higher on treatments with cattle slurry application, whereas the emission per kg applied N (EF_applied) provided no consistent effect of cattle slurry application. Similar results were also obtained in experiments on maize, where cattle slurry treatments emitted more N_2O per kg N uptake than fertiliser-only treatments (van Groenigen et al. 2004). Therefore, the emission factor based on N uptake expresses the relatively inefficient N supply of cattle slurry to crop growth better than the emission factors based on N application. Focussing on the N_2O emissions in the plant soil component of agro-ecosystems, the use of fertiliser would be preferable over the use of cattle slurry. However, this would not be valid in a whole system analysis, especially in animal systems where cattle slurry is a primary component of the N cycle.

The N surplus of cropping and farming systems is an important environmental indicator for N losses to air and water (Schroder et al. 2003). As N_2O emissions also occur with negative N surpluses, the emission per kg N surplus (EF_surplus) can have a negative value, complicating the interpretation of this type of emission factor. Moreover, in our study the EF_surplus showed no consistent relationship with the imposed treatments. Therefore this experiment does not allow a final judgment on the usefulness of this emission factor.

Conclusions

The overall mean annual N_2O emissions of all fertilised and manured treatments was 0.14% of applied N, which is low compared to the IPCC default of 1.0%. There was no consistent effect of cattle slurry application on the N_2O emission of fertiliser. Cattle slurry application increased the fertiliser N_2O emission in the first year, but had no effect in the second year. The location of the experiment on a relatively dry sandy soil has most likely contributed to the low emission levels and the lack of a consistent interaction between fertiliser and cattle slurry. With regard to the first objective, we conclude that these results don't conclusively justify an adjusted emission factor for combined application of fertiliser and cattle slurry. To minimise risks however, it is sensible to avoid simultaneous application of fertiliser and cattle slurry.

The N_2O emission per kg N uptake might have additional merit next to the emission per kg N applied, as it better represent the crops effectiveness in biomass production. The use of cattle slurry consistently increased the N_2O emission per kg N uptake. Therefore with regard to the second objective we conclude that an emission factor based on N uptake expresses the relatively inefficient N supply of cattle slurry to crop growth better than the traditional emission factor based on N application.

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