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Nitrous oxide fluxes from grassland in the Netherlands: II. Effects of soil type, nitrogen fertilizer application and grazing

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Summary

Intensively managed grasslands are potentially a large source of nitrous oxide (N_2O) in the Netherlands because of the large nitrogen (N) input and the fairly wet soil conditions. To quantify the effects of soil type, N-fertilizer application and grazing on total N_2O losses from grassland, fluxes of N_2O were measured weekly from unfertilized and mown, N fertilized and mown, and N fertilized and predominantly grazed grassland on a sand soil, a clay soil, and two peat soils during the growing season of 1992.

Total N_2O losses from unfertilized grassland were 2.5–13.5 times more from the peat soils than from the sand and clay soils. Application of calcium ammonium nitrate fertilizer significantly increased N_2O flux on all sites, especially when the soil was wet. The percentage of fertilizer N applied lost to the atmosphere as N_2O during the season ranged from 0.5 on the sand soil to 3.9 on one of the peat soils. Total N_2O losses were 1.5–2.5 times more from grazed grassland than from mown grassland, probably because of the extra N input from urine and dung. From 1.0 to 7.7% of the calculated total amount of N excreted in urine and dung was emitted as N_2O on grazed grassland. The large N_2O losses measured from the peat soils, combined with the large proportion of grassland on peat in the Netherlands, mean that these grasslands contribute significantly to the total emission from the country.

Introduction

Nitrous oxide (N_2O) is a trace gas that possibly contributes to the depletion of stratospheric ozone (Crutzen, 1970) and to global warming (Wang *et al.*, 1976). Soil is a major source of N_2O, where it is produced during microbiological nitrification and denitrification, controlled primarily by the availability of mineral nitrogen (N), oxygen (O_2) and, in case of denitrification, also mineralizable carbon (C) (Firestone & Davidson, 1989).

Soil type may effect the N_2O emission, but the relation between soil type and N_2O flux is difficult to predict because of the various chemical and physical soil properties that directly and indirectly control N_2O fluxes. In general, larger N_2O fluxes may be expected from clayey soils than from sandy soils because they are wetter and partially anaerobic from time to time. In addition, large fluxes are expected from peat soils, because they contain much organic C. Large N_2O losses were found on peat soils in the USA by Duxbury *et al.* (1982).

In the Netherlands, intensively managed grassland is a potentially large source of N_2O, because grassland covers 30% of the total surface area, the N input is large, and many soils have a high groundwater table and are therefore wet. In such intensively managed grassland, there is a large cycling of C and N due to the effects of fertilizer and manure application and the effects of grazing animals.

Results of field studies elsewhere indicate that losses of N_2O from ammonium nitrate fertilizers applied in several dressings to mown grassland are about 1–2% of the amount of N applied (Ryden, 1983; McTaggart *et al.*, 1994). Patches of urine in grazed grasslands are also a significant source of N_2O (e.g. De Klein & Van Logtestijn, 1994), predominantly because these patches contain much mineral N and also easily mineralizable organic C. At the end of the season up to 40% of the total surface area of intensively managed grasslands with about five grazing cycles may be affected by urine and about 4% by dung (Lantinga *et al.*, 1987). As a consequence, the soil contains more available N and C in grazed grasslands than in mown grasslands.

A comparison of the integral effects of grazing versus mowing on N_2O flux from grassland on various soil types and during a whole growing season has not been carried out thus far. In the monitoring study described here N_2O fluxes from grazed and mown grasslands were measured weekly during the

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growing season of 1992 on a sand soil, clay soil and two peat soils in the Netherlands. Two peat soils were included in this study because (i) more than 25% of the grassland area in the Netherlands is on peat soils and (ii) peat soils are expected to be large emitters of N_2O. The two sites on peat soil differ in mean groundwater level (GWL) and in organic N and C contents. The major factors controlling N_2O fluxes from the soil are assessed using the data on fluxes, soil, and weather. Special attention is given to the relations between N_2O fluxes and denitrification potentials (DNP) and organic C mineralization potentials (CMP) of the soils. We described the methodology of the estimation of mean fluxes and the total N_2O losses in Part I (Velthof & Oenema, 1995). Here, the effects of soil type and grassland management on N_2O fluxes and losses, based on the mean fluxes, are emphasized.

Materials and methods

Experimental sites

Fluxes of N_2O were measured from March to November 1992 at four grassland sites (Fig. 1): a sand soil near Heino (52°26′N 6°14′E), a calcareous clay soil near Lelystad (52°30′N 5°30′E), and two peat soils near Zegveld (52°08′N 4°48′E). Peat soil I had a mean GWL of 40 cm below soil surface during the experimental period, and peat soil II had a mean GWL of 55 cm. Both peat soils were clayey peats originating from reeds and sedges. Contents of total N, total C and clay, and the pH of the 0–20 cm layers, and the bulk density of the 0–30 cm layers are given for all soils in Table 1. Soil classification (FAO) and total amounts of rainfall during the experiment are also given in Table 1. Perennial ryegrass (*Lolium perenne* L.) was the dominant species in all swards.

Fig. 1. Map of the Netherlands showing the experimental sites.

Treatments

At each site the experiment was designed with complete randomized blocks, with three treatments in three replicates. The treatments were mown grass without N-fertilizer applications, mown and N-fertilized grass and predominantly grazed and N-fertilized grass. The plots on which N_2O fluxes were measured were 2.5 m × 20 m. Each grazed plot was part of a grazed area of 20 m × 20 m. Fertilizer N was applied as calcium ammonium nitrate (CAN), in six or seven dressings (Table 2). The economic optimum application rates of N fertilizer were assessed using an interactive fertilization system based on a combination of modelling and measuring soil mineral N and N uptake (Wouters & Vellinga, 1994). Fertilizer N was applied 3 days after mowing or grazing. The application rates for grazed grasslands were equal to those of mown grasslands (Table 2). The stocking density was adjusted in such a way that the dairy cattle could graze on clay and peat soils in about 1 day on the sand soil in about 2 days, when herbage yield was about 1700 kg dry matter ha^{-1}. The predominantly grazed grass was

Table 1. Soil properties of the 0–20 cm layers and total rainfall during the experimental period, of each site.

	Site			
Property	Sand	Clay	Peat I	Peat II
Total N / $g\ kg^{-1}$	2.5	2.4	16.3	18.6
Total C / $g\ kg^{-1}$	30	27	156	223
pH-KCl	5.5	7.2	5.0	4.7
Clay content ($\leqslant$2 μm) / $g\ kg^{-1}$	51	295	284	287
Dry bulk density[a] / $kg\ dm^{-3}$	1.35	1.30	0.52	0.45
Soil classification (FAO)	Fimic Anthrosol	Calcaric Fluvisol	Terric Histosol	Terric Histosol
Total rainfall / mm	520	570	540	540

[a]of the 0–30 cm layer

Table 2. Fertilizer N application rates (kg N ha^{-1}) for all sites.

	Cut number/grazing cycle							
Site	1	2	3	4	5	6	7	Total
Sand	46	61	85	32	10	32	47	313
Clay	67	58	85	24	8	35	—	277
Peat I	28	61	73	15	34	55	—	266
Peat II	0	40	53	0	4	16	48	161

mown once, at the end of the regrowth after the second grazing. Total N input by urine and dung of the grazing cattle was calculated using standard procedures and data of the amount, type and N contents of the feed consumed by the cows, the number of grazing days and the production of milk (Bussink, 1994).

Measurements of N_2O fluxes and soil variables

Vented closed flux chambers and a photo-acoustic infra-red gas analyzer and multipoint sampler directly attached to the chambers were used to measure N_2O fluxes in the field. A detailed description of procedures for the measurement and calculation of the N_2O fluxes is given in Part I (Velthof & Oenema, 1995).

The DNP is defined as the maximum rate at which nitrate (NO_3^-) will be reduced under anaerobic conditions without addition of exogenous reductant (Focht, 1978) and CMP is defined as the rate at which organic C is mineralized under aerobic conditions. The DNP and CMP were determined once, in the 0–5, 5–10, 10–20, 20–40 and 40–60 cm layers of the four soils using procedures similar to those of Burford & Bremner (1975) and Bijay-Singh *et al.* (1988). The DNP was determined at 20°C from the linear increase of the N_2O concentration in the headspace of 1-l bottles, during incubation of 100 g field moist soil to which KNO_3 was added (100 mg $NO_3^- - N$ kg^{-1} soil), in a N_2 atmosphere containing 5% acetylene (C_2H_2). The CMP was calculated from the linear increase of the concentration of carbon dioxide (CO_2) in the headspace of the bottles during aerobic incubation at 20°C of 100 g field-moist soil samples. The DNP and CMP were determined using a photo-acoustic infra-red gas analyzer for analysis of N_2O and CO_2 concentration.

Soil water content of the 0–30 cm layers was determined gravimetrically once per week by drying at 105°C for 24 h. Soil temperature was measured at a depth of 5 cm. Total soil mineral N($NH_4^+ - N + NO_3^- - N$) contents of the 0–30 layer were also determined weekly on each treatment, in four replicates. Each sample was composed of 15 cores (diameter 3 cm) from one plot. Mineral N content was analyzed after extraction of 50 ml field-moist soil in 100 ml of 1 M NaCl solution, using standard auto-analyzer techniques. Mean GWL was calculated from weekly readings of water level in 12 perforated pipes (internal diameter 4 cm) per site. The amount of rainfall was measured daily.

Mean water-filled pore space (WFPS) of the 0–30 cm soil layers was calculated to compare the moisture status of the different soils (Davidson, 1991). Standard procedures were used to calculate the density of the solid phase ρ_s, the porosity ϕ, and WFPS.

Statistical analysis

For each site, the significance of the difference between N_2O fluxes from the treatments was assessed by analysis of variance (ANOVA) and Least Significance Difference (LSD) test at 5% significance level. Variance was analyzed for each measurement time separately, with treatment as source of variation. All fluxes were transformed to natural logarithms to obtain stable variance. In case one or more of the 18 fluxes per measurement time (three treatments times six replicates) was negative (Velthof & Oenema, 1995), a value was added to all 18 fluxes to obtain only positive values with 2.0 as minimum.

For each site, multiple linear regression analyses were carried out using the following model:

$$F = \alpha + \beta N + \gamma W + \delta W^2 + \varepsilon T,$$

in which F is the N_2O flux in µg N m^{-2} h^{-1} transformed to natural logarithm, N is the mineral N content of the 0–30 cm layer in kg N ha^{-1}, W is WFPS of the 0–30 cm layer in % and T is temperature at 5 cm depth in °C. The variable W^2 was included, because the relation between WFPS and N_2O flux as suggested by Davidson (1991) can be fitted with quadratic function. All treatments were included in the regression analyses.

On pooled data of all sites, multiple linear regression analysis was carried out, using the following model:

$$F = \alpha + \beta N + \gamma W + \delta W^2 + \varepsilon T + \zeta D$$

in which D is the denitrification potential of the 0–10 cm layer in kg N ha^{-1} d^{-1}, assuming that the DNP of the 0–10 cm layer was a major factor causing the differences in N_2O fluxes between the soils. All statistical analyses were carried out using Genstat 5 (Genstat 5 Committee, 1987).

Results

DNP and CMP

For all soils, both DNP and CMP strongly decreased with increasing depth (Table 3). The largest difference was between the 0–5 and 5–10 cm layers. The DNP of the peat soils was much larger than those of the sand and clay soils. The DNP of the 0–5 cm layer was larger for the clay soil than for the sand soil, but the DNP of the deeper layers of these soils were in the same range. The CMP of the sand soil was less than that of the other soils. For all sites DNP and CMP were correlated.

Table 3. Denitrification potentials (DNP) and organic C mineralization potentials (CMP) of the 0–5, 5–10, 10–20, 20–40 and 40–60 cm layers of the soils.

Layer /cm	DNP/mg N kg^{-1} dry soil day^{-1}				CMP/mg C kg^{-1} dry soil day^{-1}			
	Sand	Clay	Peat I	Peat II	Sand	Clay	Peat I	Peat II
0–5	19	30	103	87	85	161	216	191
5–10	8	6	30	37	38	69	63	77
10–20	3	4	13	12	20	40	25	26
20–40	4	2	12	4	14	29	37	32
40–60	0	1	13	5	0	22	43	20

Site	n	Model	R^2_{adj}
Sand	68	$F = -1.0 + 0.015N + 0.04W + 0.09T$	0.34
Clay	63	$F = -10.4 + 0.028N + 0.30W - 0.0016W^2$	0.31
Peat I	73	$F = -10.8 + 0.017N + 0.24W - 0.0011W^2 + 0.20T$	0.36
Peat II	60	$F = 3.0 + 0.018N + 0.04W + 0.063T$	0.41
All	264	$F = -3.2 + 0.020N + 0.13W - 0.0007W^2 + 0.027D$	0.28

Table 4. Results of multiple linear regression analyses. Models presented are models with highest values for R^2_{adj} including only significant independent variables. See text for symbols.

However, the relation between DNP and CMP was specific to individual sites, i.e. at equal CMP, DNP was about twice as much on the peat soils than on the sand and clay soil.

N_2O fluxes

Fluxes of N_2O from unfertilized grassland on the sand and clay soils and peat soil I were small, less than 0.1 mg N m^{-2} h^{-1}. By contrast, fluxes from the unfertilized treatment on peat soil II were high, up to 1.7 mg N m^{-2} h^{-1} in April. Mineral N contents in the top 30 cm of the soil of unfertilized grassland were generally less than 35 kg N ha^{-1} in the sand and clay soils and peat soil I. Mineral N contents in unfertilized peat soil II were in the range of 30–50 kg N ha^{-1}.

Application of N fertilizer increased both mineral N contents and N_2O fluxes (Figs 2 and 3). There was no clear relation between magnitude of N_2O flux and the amount of fertilizer applied. The increase of N_2O flux after application of fertilizer lasted 1–2 weeks generally. A total of seven out of 34 weekly measured fluxes on the sand soil, eight out of 32 on the clay soil, nine out of 30 on peat soil I, and six out of 21 weekly measured fluxes on peat soil II were significantly larger on N-fertilized and mown grassland than on unfertilized and mown grassland.

Both, soil mineral N contents and fluxes of N_2O were much larger on N-fertilized and grazed grassland than on N-fertilized and mown grassland (Fig 2 and 3). Fluxes were significantly larger from grazed grassland than from mown grassland in 18 out of the 28 weekly measurements after the first grazing on the sand soil, five out of the 27 on the clay soil, one of the 23 on peat I and six out of the 21 on peat soil II.

The largest fluxes occurred when the soil was wet and the WFPs exceeded about 70%. Fluxes were smallest during the dry and warm period in June and July when WFPS of the 0–30 cm layer was less than 50%, for all sites. The GWL was much higher in the peat soils than in the sand and clay soils (Figs 2 and 3). In wet late summer and autumn, WFPS and GWL increased strongly at all sites. Peat soil I was waterlogged in November.

The percentage of variance in N_2O flux accounted for ranged from 28% for all sites to 41% for peat soil II (Table 4). Mineral N contents and WFPS showed a significant effect in all regression models. Temperature was only a significant variable in the models of the sand soil and both peat soils.

Total N_2O losses

The order of total N_2O loss during the growing season was sand soil < clay soil < peat soil I < peat soil II for almost all treatments (Fig. 4). Total N_2O losses were 1.5–6 times larger on N-fertilized grassland than on unfertilized grasslands and were 1.5–2.5 times larger on grazed grasslands than on mown grasslands.

Due to the difference in herbage yield, herbage N content (not shown) and grazing days, the amount of N excreted via urine and dung on the grassland differed strongly between the sites, ranging from 195 kg N ha^{-1} for peat soil II to 430 kg N ha^{-1} for the sand soil (Table 5). The amount of N excreted via urine was about three times that via dung. The N-fertilizer-derived N_2O losses ranged from 1.7 kg N ha^{-1} for the sand soil to 6.2 kg N ha^{-1} for both peat soils, or 0.5 to 3.9 when expressed in % of N applied as CAN (Table 6). The grazing-derived N_2O losses were larger than the N-fertilizer-derived N_2O losses, except for peat soil I (Table 6).

At all sites, the total N_2O loss increased with increasing N input via N fertilizer, dung and urine (Fig. 5). Remarkably, total N_2O losses from grazed grass on sand soil, the treatment

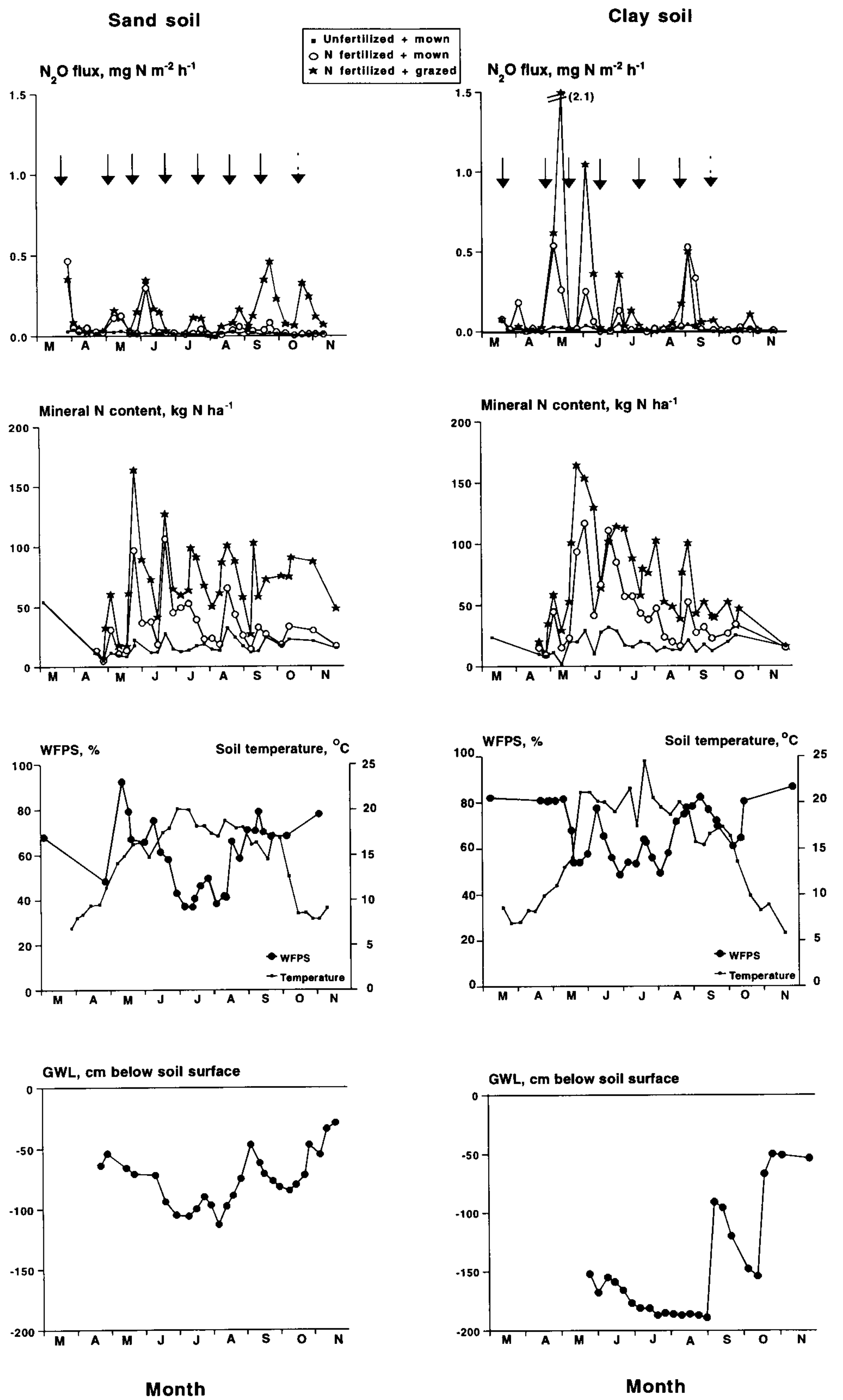

Fig. 2. Time course of N_2O fluxes, mineral N contents and WFPS of the 0–30 cm soil layer, soil temperature at 5 cm depth and GWL for the sand soil and the clay soil. Thick arrows indicate time of N application and grazing and dotted arrows time of grazing without N application.

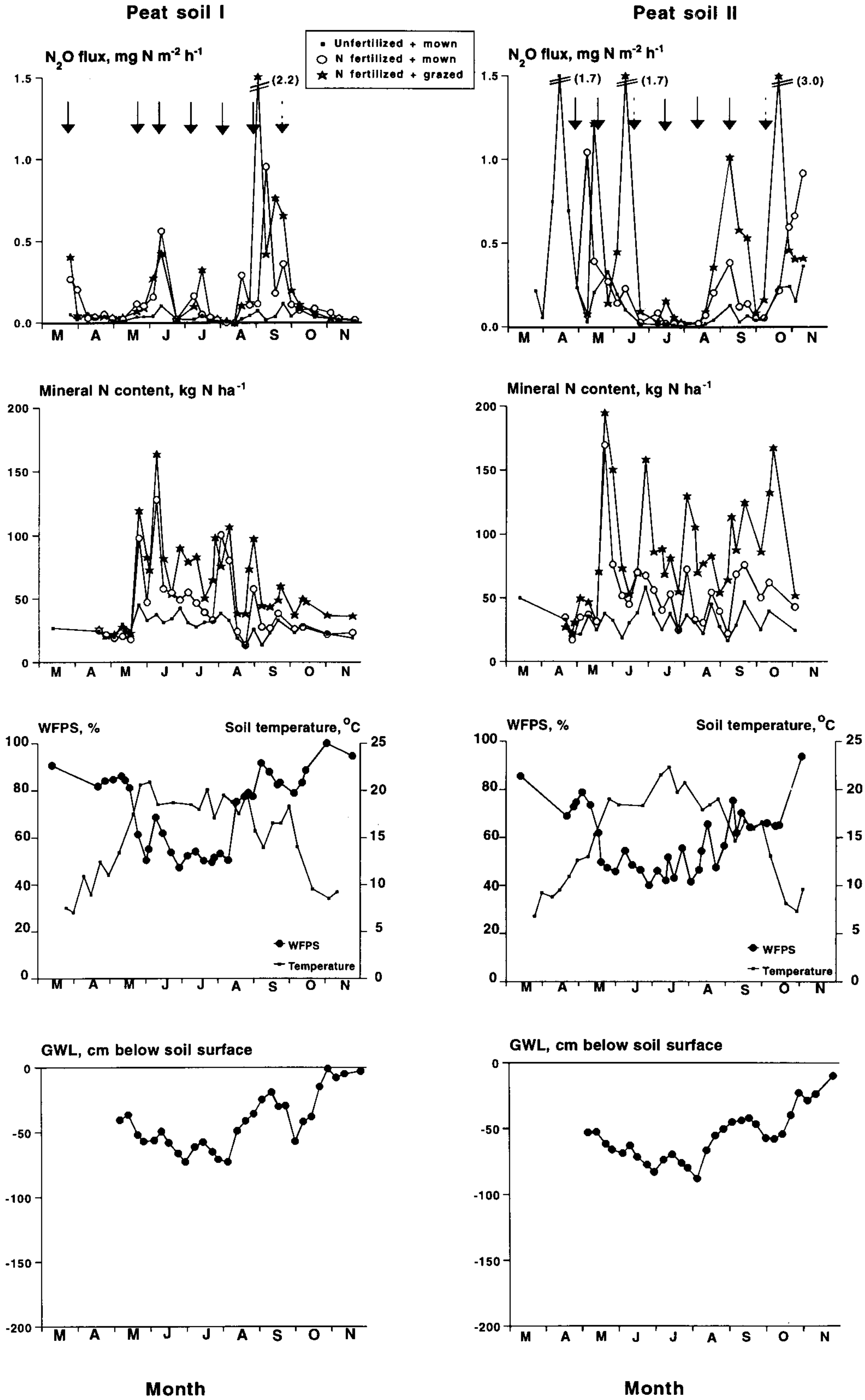

Fig. 3. Time course of N_2O fluxes, mineral N contents and WFPS of the 0–30 cm soil layer, soil temperature at 5 cm depth and GWL for the peat soil I and peat soil II. Thick arrows indicate time of N application and grazing and dotted arrows time of grazing without N application.

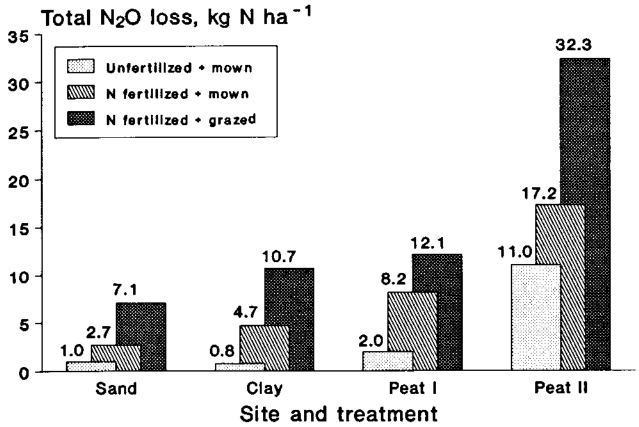

Fig. 4. Total N_2O losses during the experimental period March–November 1992, for all sites and treatments.

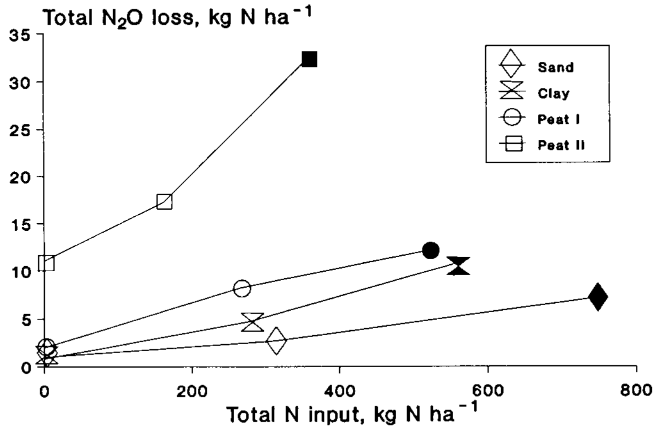

Fig. 5. Relationship between total N_2O loss during the experimental period and N input via N fertilizer, urine and dung, for all sites. Open symbols represent mown treatments and closed symbols represent grazed treatments.

with the largest N inputs via N fertilizer, urine and dung, were less than total N_2O losses from unfertilized grassland on peat soil II, with no N input via fertilizer, urine and dung.

Discussion

Soil type and N_2O fluxes and losses

The decrease in DNP and CMP with increasing soil depth is related to the distribution of easily mineralizable organic C in grassland soils. The relation between CMP and DNP was not the same for all soils, suggesting that other factors than CMP controlled DNP in this study. This is in contrast with studies of Burford & Bremner (1975) and Bijay-Singh *et al.* (1988) who found a relation between DNP and CMP applicable for all the soil they studied. Differences in the presence and activity of bacterial populations may have contributed to the differences between the soils.

There was only a weak relation between DNP or CMP and total N_2O losses from unfertilized and mown grassland. Regression analyses indicate that DNP was a significant variable (Table 4), but it accounted for little of the variance. Yet, DNP and CMP, and total N_2O losses from unfertilized grassland were much larger on the peat soils than on the sand and clay soils, and there were remarkable differences between the two peat soils. Differences between the peat soils must be attributed to differences in GWL and actual mineralization rates. The larger mineral N content in the top 30 cm (Fig. 3) and the smaller economically optimum N application rate (Table 2) both suggest that actual mineralization rates were larger on peat soil II than on peat soil I. Lowering the GWL of peat soils has been shown greatly to increase N mineralization rates (Williams & Wheatley, 1988) and N_2O emission (Martikainen *et al.*, 1993). Results of the present study also suggest that small differences in GWL (Fig. 3) may contribute to large differences in N_2O emission. However, differences in other soil variables might also have contributed. Peat soil I and peat soil II lie 1 km apart and were managed differently prior to this experiment. Generally, largest fluxes were found in the range of 60–80% WFPS, which is in agreement with Davidson (1991), who suggested that the relation between WFPS and N_2O flux has an optimum. In three out of the five models of Table 4 $(WFPS)^2$ was a significant variable.

Table 5. Number of cow grazing days and calculated amounts of N excreted via dung and urine on the grazed grassland, for all sites and the whole growing season.

Site	Number of cow grazing days	Total excreted N/kg N ha^{-1} Urine	Dung	Total
Sand	783	320	110	430
Clay	497	210	70	280
Peat I	475	185	70	255
Peat II	362	145	50	195

Table 6. N-fertilizer-derived* and grazing-derived** N_2O losses in kg N ha^{-1} and in % of N applied as CAN or N excreted via dung and urine.

Site	N-fertilizer-derived N_2O loss /kg N ha^{-1}	% of N applied	Grazing-derived N_2O loss /kg N ha^{-1}	% of N excreted
Sand	1.7	0.5	4.4	1.0
Clay	3.9	1.4	6.0	2.1
Peat I	6.2	2.3	3.9	1.5
Peat II	6.2	3.9	15.1	7.7

*losses from fertilized and mown grassland minus losses from unfertilized and mown grassland.

**losses from fertilized and grazed grassland minus losses from fertilized and mown grassland.

The large differences in total N_2O loss between the two peat soils was due in part to the large differences in N_2O fluxes in spring and autumn. During these periods WFPS of peat soil II was lower (< 80%) than of peat soil I (> 80%). Perhaps, N_2O was a more important end product of denitrification for the peat soil II than for the peat soil I.

Effect of N fertilizer application on N_2O fluxes and losses

At all sites, application of N fertilizer increased N_2O fluxes, generally for a maximum of two weeks. The flux patterns depicted in Figs 2 and 3 are typical for N_2O fluxes from grasslands fertilized in several N dressings (Ryden, 1983; McTaggart *et al.*, 1994). This pattern is due mainly to fluctuations in mineral N content in the soil (Figs 2 and 3), caused by fertilizer application, a rapid N uptake by grass roots and possibly microbial biomass, and losses by leaching, denitrification and volatilization. In all regression models (Table 4), mineral N content was a highly significant variable.

The N-fertilizer-derived N_2O losses of the sand (0.5%) and clay soil (1.4%) are in the range of those reported in literature. The fertilizer-derived N_2O losses from the peat soils (2.3 and 3.9%) are large compared with those previously reported. This indicates that intensively managed grassland on peat soils is a large N_2O source.

Effect of grazing on N_2O fluxes and losses

Because the fertilizer applications were equal for the grazed and mown swards, the differences in N_2O fluxes and losses between the mown and grazed treatment (Figs 2, 3, 4 and 5) have to be attributed to the effects of the grazing animal, i.e. the N input via urine and dung and compaction of the soil by treading. The effect of excretal N is also shown by the increased soil mineral N contents of the grazed swards relative to those of the mown swards (Figs 2 and 3).

Dung and urine patches are significant sources of N_2O, because they contain much mineral N and mineralizable N and C. Denitrification losses from dung-affected and urine-affected areas have been shown to be large during wet conditions in autumn (Ryden, 1986). Production of N_2O in urine patches may be enhanced due to inhibitory effects of large ammonia (NH_3) concentrations on nitrification leading to nitrite (NO_2^-) accumulation (Monaghan & Barraclough, 1992). In soil, NO_2^- can be biologically and chemically denitrified into N_2O (Firestone & Davidson, 1989). Moreover, grazing cows compact the soil by treading, thereby decreasing O_2 diffusivity in the soil, which may result in an increased denitrification rate and N_2O production. The large grazing-derived N_2O losses in comparison to the fertilizer-derived N_2O losses (Table 6) suggest that these mechanisms may have played a role in grazed grassland. For the sand and clay soils and peat soil II, the grazing-derived N_2O losses, expressed in percentage of the N input via urine and dung, were roughly a factor 2 larger than the fertilizer-derived N_2O losses, expressed as percentage of the N input via N fertilizer. This difference may be the result of the stimulating effects of compaction of the soil and of dung and urine on N_2O flux from the grazed soil. In addition, the much larger total N input of grazed grassland compared to mown grassland is likewise important, because N_2O becomes a more important end product of denitrification when NO_3^- concentrations increase (Firestone & Davidson, 1989). For the peat soil I, grazing-derived N_2O loss was somewhat smaller than fertilizer-derived N_2O loss, in terms of % of the N input. The exact reason for this is yet unknown.

In conclusion, this study shows that both grassland management and soil type are major factors controlling N_2O losses from grassland. The strong increase of N_2O losses due to grazing shows that the effect of grazing has to be considered in N_2O budget calculations. The large N_2O losses from the peat soils combined with the fact that more than 25% of the grassland area in the Netherlands is on peat soils, indicate that grasslands on peat soils are a major source of N_2O in the Netherlands.

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