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Seasonal variations in nitrous oxide losses from managed grasslands in The Netherlands

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Abstract

Seasonal and interannual variations in nitrous oxide (N_2O) losses from agricultural soils hamper the accurate quantification of the N_2O source strength of these soils. This study focuses on a quantification of seasonal and interannual variations in N_2O losses from managed grasslands. Special attention was paid to N_2O losses during the growing season and off-season as affected by grassland management. Fluxes of N_2O from grasslands with three different types of management and on four different soil types in the Netherlands were measured weekly during two consecutive years, using flux chambers. There were distinct seasonal patterns in N_2O losses, with large losses during spring, summer, and autumn but relatively small losses during the winter. These seasonal variations were related to fertilizer N application, grazing and weather conditions. Measurements of N_2O concentrations in soil profiles showed that a rise in groundwater level was accompanied by increased N_2O concentrations in the soil. Disregarding off-season losses would underestimate total annual losses by up to 20%, being largest for unfertilized grassland and smallest for N-fertilized grazed grassland. Total annual N_2O losses ranged from 0.5 to 12.9 kg N ha^{-1} yr^{-1} for unfertilized grasslands to 7.3 to 42.0 kg N ha^{-1} yr^{-1} for N-fertilized grazed grasslands. Despite the considerable interannual variations in N_2O losses, this study indicates that the results of measurements carried out in one year have predictive power for estimating N_2O losses in other years.

Introduction

There is still considerable uncertainty in the global nitrous oxide (N_2O) budget (Bouwman, 1995). Agricultural soils are suggested to be a major source of nitrous oxide (Bouwman, 1995), but quantification of its importance is hampered by the huge temporal and spatial variations in the flux (e.g. Clayton et al., 1994; Conrad et al., 1983; Webster and Dowdell, 1982). To overcome the uncertainties related to temporal variability, continuous measurements are needed throughout the whole year. In practice, most measurements are not continuous and focus on the growing season (e.g. Conrad et al., 1983; Ryden, 1983). The off-season period is neglected as being of minor importance. However, a study of Bouwman (1995) suggests, in part, that the off-season cannot be neglected when assessing total emissions and fertilizer-derived N_2O losses.

Distinct seasonal patterns of N_2O losses from grassland have been observed, caused by weather conditions and grassland management (e.g. McTaggart et al., 1994; Webster and Dowdell, 1982). Generally, losses are much higher during the growing season (spring, summer and autumn) than during the off-season (winter). The off-season losses from grassland are likely to be related to weather conditions and residual effects of fertilizer N and excretal N from grazing cattle, but little is known about these effects.

Improved knowledge of seasonal and interannual variations of N_2O losses from managed grasslands will improve the reliability of estimates of N_2O losses from grasslands. It can also help to set up strategies for field measurements in which N_2O losses are quan-

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tified. This study focuses on the relative importance of off-season N_2O losses as a function of previous grassland management. We hypothesize that N_2O losses in the off-season are strongly related to residual effects of fertilizer N and grazing in the previous growing season, and that N_2O loss in the off-season increases in the following order: unfertilized mown grassland < N fertilized mown grassland < N-fertilized grazed grassland. We expect that groundwater level has a large effect on N_2O losses, because for example a shallow groundwater level will limit mineralization, nitrification and, thereby, denitrification rates, and it will also decrease the N_2O/N_2 ratio in denitrification (e.g. Martikainen et al., 1993). To be able to detect its effect, groundwater level was recorded together with N_2O concentrations in the soil profiles, and N_2O surface fluxes.

Results of weekly flux measurements for two consecutive years on four sites with three management strategies each were used to calculate the effects of seasons, years, fertilizer N application and grazing on the size of the N_2O losses.

Materials and methods

Experimental set-up

A detailed description of the sites and experimental set-up is given by Velthof and Oenema (1995a, b). Briefly, N_2O fluxes were measured on intensively-managed grasslands at four contrasting sites: a sand soil in Heino (FAO classification : Fimic Anthrosol), a clay soil in Lelystad (Calcaric Fluvisol) and two peat soils in Zegveld (Terric Histosols), during the period March 1992 to March 1994. Major difference between the two peat soils was the difference in groundwater level (Table 1).

All grasslands had *Lolium perenne* swards and had been intensively managed for more than 10 years before the study was started. There were three grassland management treatments on each site, namely mowing without N fertilizer application, mowing with N fertilizer application and predominantly grazing with N fertilizer application. At each site the experiment was designed with complete randomized blocks, with the three management treatments in three replicates. Amounts of fertilizer N were assessed by using an interactive fertilization system aiming at economically optimum amounts, with equal portions on the mown and grazed swards (Vellinga et al., 1995). Fertilizer N was applied as calcium ammonium nitrate (CAN) in six or seven dressings per year. Total fertilizer N application rates ranged from 161 kg N ha^{-1} for peat soil II in 1992 to 464 kg N ha^{-1} for peat soil I in 1993.

Grazing started at a target herbage yield of 1700 kg dry matter ha^{-1}. Stocking density was adjusted in such a way that the dairy cows were able to graze the sward for two days. Total N input via urine and dung excreted by the grazing cattle was calculated using standard calculation procedures (Bussink, 1994).

Fluxes and losses of N_2O

Fluxes of N_2O were measured in six replicates on a weekly basis using circular vented closed flux chambers with an internal diameter of 20 cm and a height of 15 cm, as described in detail by Velthof and Oenema (1995a). Concentrations of N_2O in the headspace of each flux chamber were determined in situ four times, with 10-minute intervals, using a photo-acoustic spectroscopic infra-red gas analyzer of Brüel and Kjær, directly attached to the chambers. The relative standard deviation of replicate N_2O analyses with the gas analyzer was about 5% in the range of 300–1000 μL N_2O m^{-3} under field conditions. Flux of N_2O was calculated from the linear increase in N_2O concentration in the headspace of the chambers. All flux measurements at one site were carried out within 3 hours, usually between 9.00 and 12.00 hours. Mean fluxes ($n = 6$) were calculated as arithmetic means (Velthof and Oenema, 1995a). Total N_2O losses were estimated by interpolation of the mean fluxes and integration of the area of the curve.

There are a number of possible limitations associated with closed flux chamber techniques when used for the quantification of total N_2O losses from soils, as discussed for example by Mosier (1989). A discussion of the advantages and possible methodological problems of the present flux chamber technique is given by Velthof and Oenema (1995a). To be able to quantify total N_2O losses of three different management treatments at four different grassland sites during a period of two years, weekly flux measurements using flux chambers in six replicates per treatment was the maximum we could achieve.

Concentration of N_2O in the soil, weather conditions and soil variables

Concentrations of N_2O in the soil atmosphere were measured at 5 depths (0–10,10–20, 20–30, 30–40 and 40–50 cm) in N-fertilized mown grassland on the sand

Table 1. Seasonal variations in rainfall, soil temperature at 5 cm depth, groundwater level (GWL) and N input via N fertilizer and via urine and dung, for March–May (spring), June–August (summer), September–November (autumn), and December–February (winter) of both years

Site and	1992–1993				1993–1994			
variable	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Total rainfall (mm)								
Sand	201	239	244	184	135	293	309	258
Clay	183	259	329	222	113	267	313	238
Peat I and II	146	257	272	145	102	281	256	255
Range in soil temperature (° C)								
Sand	6.9–16.4	14.8–20.1	7.9–17.3	1.2–6.0	3.0–17.9	14.6–17.8	0.4–15.5	2.8–6.0
Clay	6.9–21.1	17.5–24.5	5.8–17.4	0.9–5.2	0.8–17.1	14.3–22.2	0.5–14.9	1.7–5.1
Peat I	7.0–20.6	17.1–20.9	8.5–18.3	0.6–7.6	2.8–15.2	14.3–17.9	2.6–16.1	0.6–6.0
Peat II	6.8–15.3	17.9–22.3	7.3–16.7	0.6–7.9	1.2–17.7	14.9–19.1	0.6–17.7	0.2–7.0
Range in GWL (cm)								
Sand	49–71	75–122	8–86	10–65	45–80	24–95	20–49	0–62
Clay	152–169	155–189	54–154	47–58	93–99	60–90	57–69	26–83
Peat I	37–57	36–73	1–57	5–18	38–58	19–61	6–37	2–19
Peat II	53–66	56–88	10–58	16–34	48–67	37–74	13–57	2–40
N input[a] (kg N ha^{-1})								
Sand	192 (136)	74 (147)	47 (147)	0 (0)	239 (112)	136 (121)	49 (69)	0 (0)
Clay	210 (135)	67 (102)	0 (43)	0 (0)	251 (93)	187 (157)	0 (43)	0 (0)
Peat I	89 (34)	123 (152)	55 (68)	0 (0)	230 (89)	234 (130)	0 (30)	0 (0)
Peat II	93 (68)	20 (76)	48 (50)	0 (0)	160 (77)	123 (86)	40 (58)	0 (0)

[a]Total N input via N fertilizer for N-fertilized grasslands. In parentheses: total N input via dung and urine, for grazed grasslands.

soil and on peat soil I, using sampling probes constructed of perforated PVC pipes of 7.5 cm internal diameter and 50 cm length. Each pipe consisted of 5 isolated compartments of 10 cm length and a volume of 0.44 L. The concentration of N_2O in each compartment was measured via two tygon tubes directly attached to the inlet and outlet of a photo-acoustic spectroscopic infrared gas analyzer. The sample probes remained at the same place during the experimental period. Measurements were carried out weekly between August 1992 and July 1993, except in periods with high groundwater levels.

Mean soil temperature at 5 cm depth was determined weekly (during flux measurements) and rainfall was recorded daily, at all sites. Mean groundwater level was calculated weekly from water level readings in 12 perforated pipes (I.D. 4 cm) per site. Soil mineral N (NH_4^+ - N + NO_3^--N) contents of the 0–30 cm layer of each treatment were determined weekly in 4 replicates during the growing season and about monthly during winter. Each sample was composed of 15 cores (diameter 3 cm) per plot. In the first year of the experiment, 50 mL field moist soil was extracted in 100 mL of 1 *M* NaCl solution. In the second year, 10 g dry soil (24 hours drying at 40°C) was extracted in 100 mL 0.01 *M* $CaCl_2$ (Vellinga et al., 1995). In the extracts, NH_4^+ and NO_3^- were analyzed using standard auto-analyzer techniques (Houba et al., 1989).

Results

Seasonal variations in weather conditions, groundwater levels and nitrogen input

Both years had similar patterns of rainfall, with a dry spring and a wet summer and autumn (Table 1). Winter was dry in 1992–1993. Highest soil temperatures at 5 cm depth were found in summer and ranged from 20° to 25°C (Table 1). Both winter periods were rela-

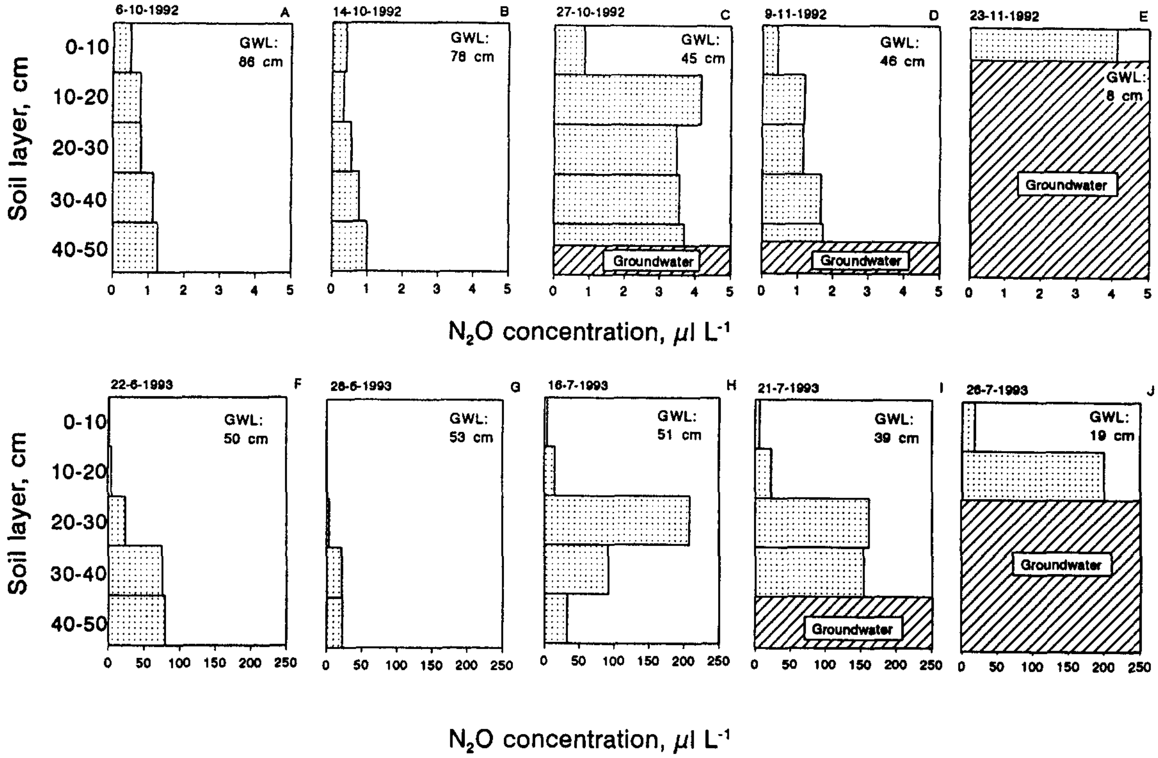

Figure 1. Typical N_2O concentration profiles in the soil of N-fertilized mown grassland showing the effect of groundwater level (GWL) rise on N_2O concentrations. In Figures **A** – **E**, concentration profiles in the sand soil and in Figures **F** – **J**, concentration profiles in peat soil I. Note differences in scales of X-axes in the upper and lower graphs.

tively genial; there were no long periods of frost and the soil temperatures at 5 cm depth exceeded 0°C on all occasions. However, the uppermost few cm of the soil were frozen sometimes during flux measurements. The median groundwater water level during the whole experimental period was 61 cm for the sand soil, 73 cm for the clay soil, 30 cm for peat soil I and 48 cm for peat soil II.

For all sites, groundwater levels were highest during autumn and winter, in both years (Table 1). Peat soil I was often nearly flooded during autumn and winter. Application of N fertilizer was concentrated in spring and summer (Table 1). The N input via dung and urine from grazing dairy cattle was largest in spring and summer (Table 1).

Concentration of N_2O in the soil

Typical N_2O concentration profiles of the N-fertilized mown treatment of the sand soil and peat soil I are presented in Figure 1. Generally, concentrations increased with increasing soil depth. Concentrations were more than an order of magnitude higher in the peat soil than in the sand soil.

Effects of a rising groundwater level on N_2O concentrations in the sand soil are illustrated in Figures 1A to 1E, for the period 6 October to 23 November 1992. The rise in groundwater level between 14 and 27 October from 78 cm to 45 cm below soil surface coincided with an increase in N_2O concentration, at all depths. The strong increase in groundwater level in the second half of November markedly increased N_2O concentrations in the 0–10 cm layer (Fig. 1E). This increase was accompanied with a strong increase in surface N_2O flux (not shown). The latest application of N fertilizer was 10 September, and soil temperature at 5 cm depth remained similar, 8–12°C, between 6 October and 23 November, suggesting that N fertilizer application and changes in soil temperature were not involved in the changes in N_2O concentrations.

Variations in N_2O concentrations in peat soil I during the period 22 June to 26 July 1993 (Figs. 1F to 1J) suggest that the 20–30 cm soil layer contained a major N_2O source. After N fertilizer application on 9 July and just before the rapid rise in groundwater level, N_2O concentration in the 20-30 cm layer increased from less than 20 to more than 200 $\mu L\ L^{-1}$. Apparently, optimum conditions for N_2O production were cre-

Table 2. Seasonal averaged losses of N_2O in kg N ha^{-1} and, in parentheses, as percentage of the total annual loss, for March–May (spring), June–August (summer), September–November (autumn), and December–February (winter) of both years

Site and treatment	1992–1993 Spring	Summer	Autumn	Winter	1993–1994 Spring	Summer	Autumn	Winter
Unfertilized mown								
Sand	0.4 (33)	0.3 (25)	0.3 (25)	0.2 (17)	0.3 (30)	0.5 (50)	0.1 (10)	0.1 (10)
Clay	0.3 (30)	0.3 (30)	0.2 (20)	0.2 (20)	0.2 (40)	0.3 (60)	0.0 (0)	0.0 (0)
Peat I	0.4 (19)	0.7 (33)	0.8 (38)	0.2 (10)	0.5 (28)	0.9 (50)	0.4 (22)	0.0 (0)
Peat II	7.3 (57)	1.0 (8)	3.0 (23)	1.6 (12)	0.9 (21)	1.0 (24)	1.5 (36)	0.8 (19)
N-fertilized mown								
Sand	1.0 (32)	1.0 (32)	0.9 (29)	0.2 (6)	0.8 (12)	4.3 (65)	1.3 (20)	0.2 (3)
Clay	2.2 (44)	1.2 (24)	1.3 (26)	0.3 (6)	2.0 (77)	0.6 (23)	0.0 (0)	0.0 (0)
Peat I	1.1 (14)	3.0 (38)	3.7 (46)	0.2 (2)	1.2 (12)	6.8 (71)	1.5 (16)	0.1 (1)
Peat II	9.4 (47)	2.1 (10)	6.7 (33)	2.0 (10)	3.0 (19)	2.5 (16)	8.5 (53)	1.9 (12)
N-fertilized grazed								
Sand	1.3 (18)	2.1 (29)	3.5 (48)	0.4 (5)	3.1 (23)	8.3 (63)	1.7 (13)	0.1 (1)
Clay	5.9 (56)	3.2 (30)	1.2 (11)	0.3 (3)	14.4 (89)	1.2 (7)	0.5 (3)	0.0 (0)
Peat I	0.9 (8)	4.6 (39)	6.1 (51)	0.3 (2)	1.8 (10)	11.8 (68)	3.7 (21)	0.0 (0)
Peat II	9.4 (26)	7.1 (20)	15.4 (43)	4.1 (11)	2.6 (6)	11.4 (28)	25.2 (61)	1.8 (4)

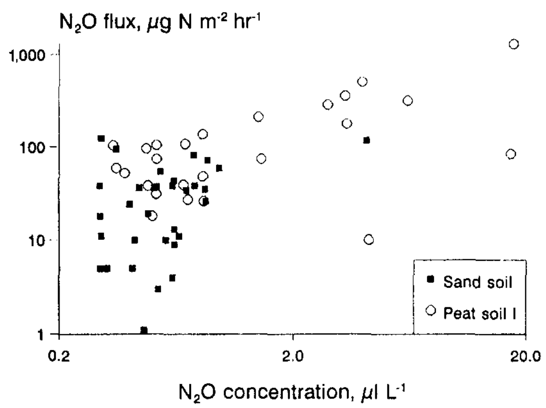

Figure 2. Relationship between N_2O concentration in the 0–10 cm soil layer and surface N_2O flux, for N-fertilized mown grassland on the sand soil and peat soil I. Note logarithmic scales.

ated in this layer where the descending NO_3^- front met the rising anaerobic front, during periods with heavy rainfall and rising groundwater levels. The rapid rise in groundwater level in the second half of July was accompanied by a strong increase in N_2O concentrations in the 0–20 cm soil layer (Fig. 1J) and in surface N_2O flux (not shown).

Flux of N_2O tended to increase with increasing N_2O concentration in the 0–10 cm layer (Fig. 2). The determination coefficient (R^2) between log-transformed N_2O concentration in the 0–10 cm layer and log-transformed surface N_2O flux was 0.23 for the sand soil (n = 33) and 0.45 for the peat soil (n = 25).

Seasonal variations in N_2O losses and soil mineral N contents

On all sites, N_2O fluxes from unfertilized mown grassland were generally smaller in the off-season (winter) than in the growing season (spring, summer, autumn) (Fig. 3). Losses of N_2O from the sand soil, clay soil and peat soil I were $\leq$ 0.2 kg N ha^{-1} during winter; those from peat soil II amounted to 1.6 and 0.8 kg N ha^{-1} in the first and second winter, respectively (Table 2). Significant fluxes were measured on peat soil II at times that the surface of the soil was frozen, suggesting that the subsoil was a source of N_2O. Mineral N contents in the top 30 cm of unfertilized mown grasslands showed seasonal patterns, with generally higher contents during the growing season than during winter (Fig. 3). Mineral N contents were much higher in peat soil II than in the other soils (Fig. 3).

Seasonal patterns in N_2O losses and mineral N contents were much more distinct for N-fertilized than for unfertilized grasslands (Fig. 4 and Table 2). Losses of N_2O were much larger in the growing season than in the off-season. Peak fluxes after N fertilizer application lasted 1–3 weeks, after which fluxes generally

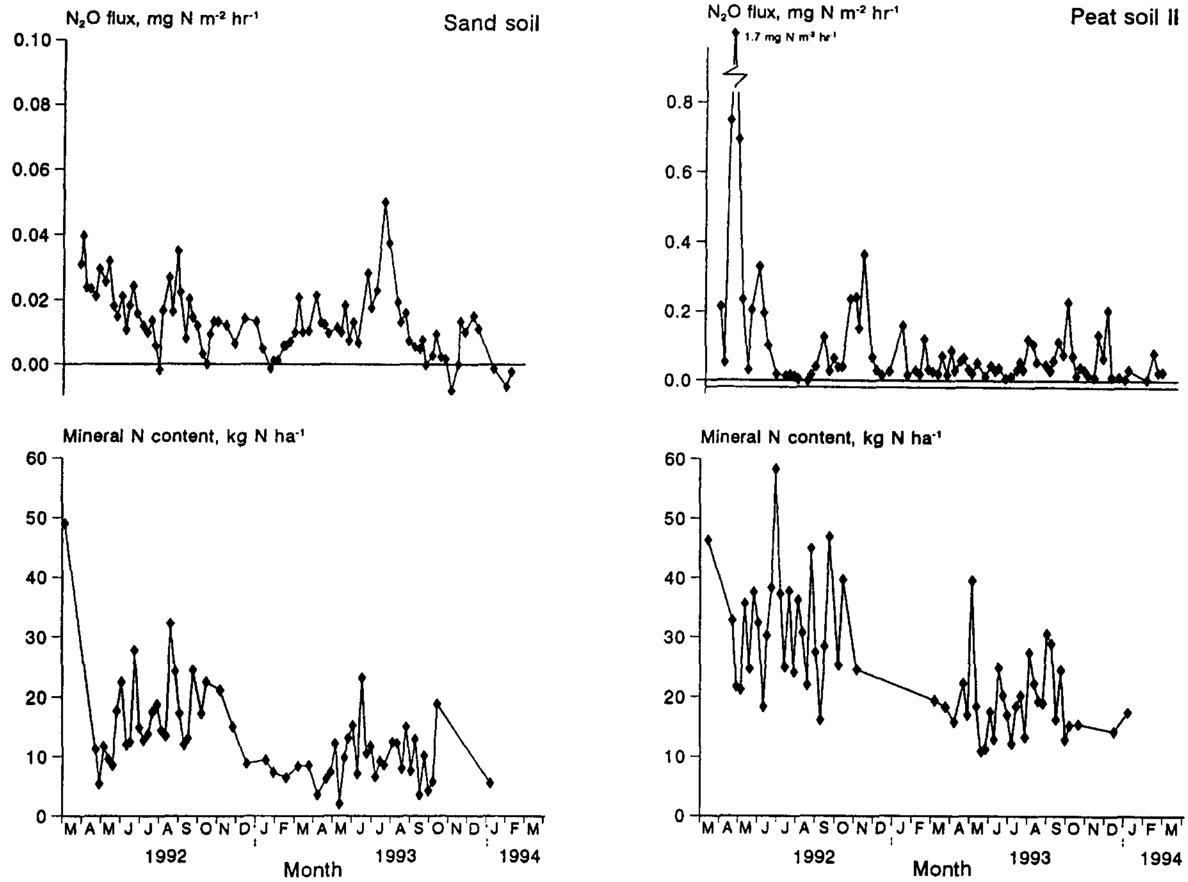

Figure 3. Time course of N_2O fluxes and mineral N contents for unfertilized mown grassland on two contrasting sites, i.e. the sand soil and peat soil II. Note differences in scale of the Y-axes of the upper graphs.

decreased to levels close to those of unfertilized grassland. Small fluxes were found during dry periods in summer and during winter. In winter, losses from N-fertilized mown grasslands were similar to or slightly larger than those from unfertilized mown grasslands (Table 2).

Fluxes and total losses of N_2O were much larger from grazed grasslands than from mown grasslands (Fig. 4 and Table 2). Differences were most pronounced during summer and autumn, except for the clay soil where largest losses occurred during spring. During winter, fluxes from grazed grassland were similar to or slightly larger than those from mown grassland.

Soil mineral N concentrations in grazed grasslands were high in the growing season but decreased in autumn and winter to a level similar to or slightly higher than those of mown grasslands (Table 3 and Fig. 4). Mineral N contents in autumn were in the order: unfertilized mown < N-fertilized mown < N-fertilized grazed grasslands for all sites and both years (Table 3).

Total annual N_2O losses and interannual variations

Annual losses from the sand soil, clay soil and peat soil I ranged from 0.5–2.1 kg N ha^{-1} yr^{-1} for unfertilized mown grassland to 7.3–17.3 kg N ha^{-1} yr^{-1} for N-fertilized grazed grassland (Table 4). Annual losses from peat soil II were much larger, ranging from 4.2–12.9 kg N ha^{-1} for unfertilized mown grassland to 36.0–41.0 kg N ha^{-1} for N-fertilized grazed grassland, despite the fact that N input was much lower than on the other sites (Table 4).

Losses of N_2O from unfertilized mown grasslands were larger in the first year than in the second year at all sites (Table 4). By contrast, losses from grazed grassland were larger in the second year than in the first year, for all sites. Results for N-fertilized mown

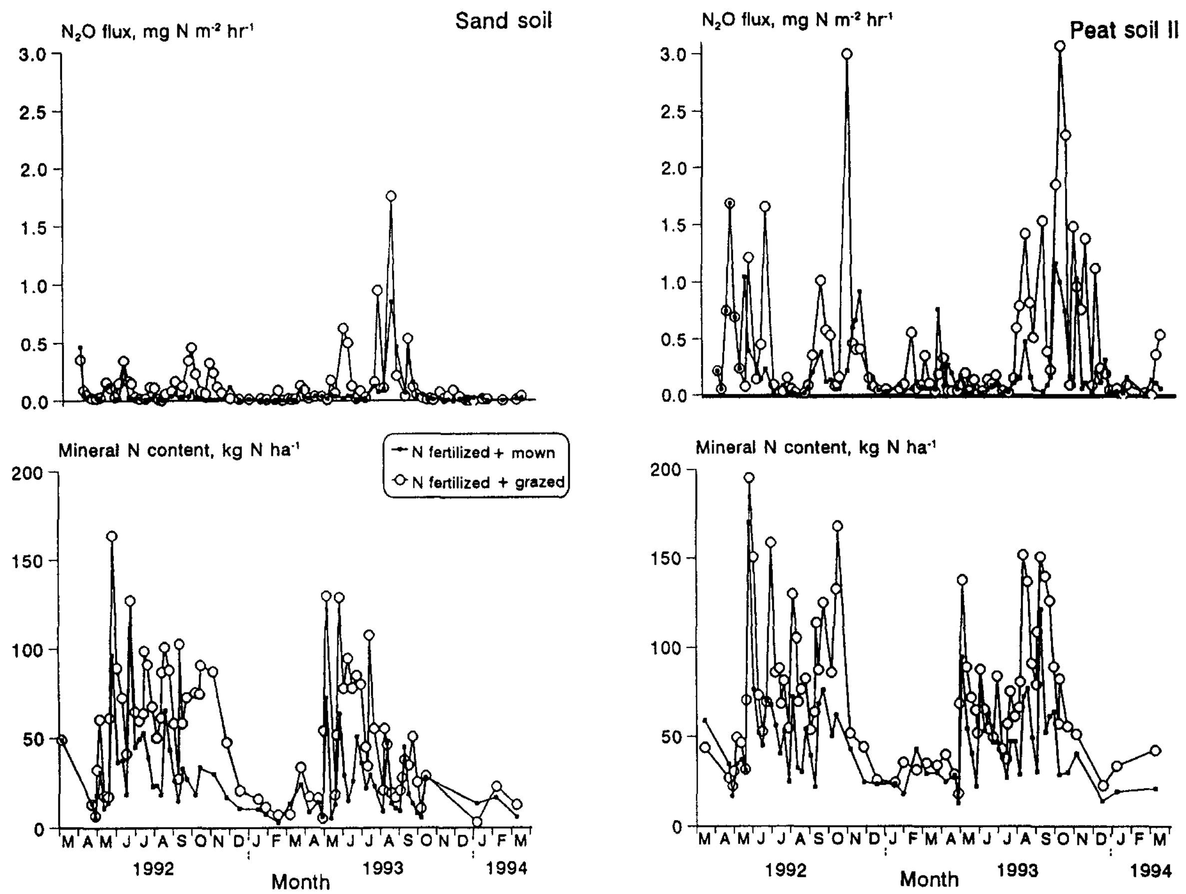

Figure 4. Time course of N_2O fluxes and mineral N contents for N-fertilized mown and N-fertilized grazed grassland on two contrasting sites, i.e. the sand soil and peat soil II.

grassland were intermediate; two sites showed larger losses in the first year and two in the second year.

The percentage of fertilizer N lost as N_2O on N-fertilized mown grassland, averaged over the two years, ranged from about 1% for the sand and clay soils to 3.9% for peat soil II (Table 4). For the clay soil and both peat soils, the percentage of fertilizer N lost as N_2O was larger in the first than the second year. The percentage of dung and urine N emitted as N_2O was larger than the percentage of fertilizer N emitted as N_2O, and was larger in the second than in the first year, for all sites.

Discussion

Variations in N_2O concentration in the soil

Temporal variations in N_2O concentrations in soils have been attributed to N fertilizer applications (Webster and Dowdell, 1982), changes in oxygen concentra-

Table 3. Mineral N contents in kg N ha^{-1} in grasslands in the middle of October and in the middle of December in both years, for all sites and treatments

Site	Treatment	1992		1993	
		October	December	October	December
Sand	Unfertilized mown	22	9	19	6
	N-fertilized mown	33	11	28	14
	N-fertilized grazed	75	21	29	3
Clay	Unfertilized mown	25	10	6	10
	N-fertilized mown	34	13	13	14
	N-fertilized grazed	33	12	28	26
Peat I	Unfertilized mown	30	9	20	15
	N-fertilized mown	28	11	26	24
	N-fertilized grazed	50	21	34	32
Peat II	Unfertilized mown	40	-	15	14
	N-fertilized mown	62	23	30	14
	N-fertilized grazed	133	26	56	23

Table 4. Total annual N_2O losses and N input via fertilizer, urine and dung, for all sites and treatments and both years

Site	Treatment	March 1992 – March 1993			March 1993 – March 1994			Annual average		
		N input	N_2O loss		N input	N_2O loss		N input	N_2O loss	
		(kg N ha^{-1})	(kg N ha^{-1})	(% of N-input)[a]	(kg N ha^{-1})	(kg N ha^{-1})	(% of N-input)	(kg N ha^{-1})	(kg N ha^{-1})	(% of N-input)
Sand	Unfertilized mown	0	1.2	-	0	1.0	-	0	1.1	-
	N-fertilized mown	313	3.1	0.6	426	6.6	1.3	370	4.9	1.0
	N-fertilized grazed	753	7.3	0.8 (1.0)	727	13.2	1.7 (2.2)	735	10.3	1.2 (1.5)
Clay	Unfertilized mown	0	1.0	-	0	0.5	-	0	0.8	-
	N-fertilized mown	277	5.0	1.4	437	2.6	0.5	357	3.8	0.9
	N-fertilized grazed	557	10.6	1.7 (2.0)	730	16.1	2.1 (4.6)	644	13.4	2.0 (3.3)
Peat I	Unfertilized mown	0	2.1	-	0	1.8	-	0	2.0	-
	N-fertilized mown	266	8.0	2.2	464	9.6	1.7	365	8.8	1.9
	N-fertilized grazed	521	11.9	1.9 (1.5)	712	17.3	2.2 (3.1)	617	14.6	2.1 (2.3)
Peat II	Unfertilized mown	0	12.9	-	0	4.2	-	0	8.6	-
	N-fertilized mown	161	20.2	4.5	323	15.9	3.6	242	18.1	3.9
	N-fertilized grazed	356	36.0	6.5 (8.1)	544	41.0	6.8 (11.4)	450	38.5	6.7 (9.8)

[a]Expressed as: (N_2O loss from N-fertilized mown grassland - N_2O loss from unfertilized mown grassland) / (amount of applied fertilizer N). In parentheses: percentage of dung and urine N emitted as N_2O expressed as: (N_2O loss from N-fertilized grazed grassland - N_2O loss from N-fertilized mown grassland) / (amount of emitted dung and urine N).

tion in the soil (Egginton and Smith, 1986) and rainfall (Goodroad and Keeney, 1985). The present study suggests that changes in N_2O concentration profiles were related, in part, to changes in groundwater level. A rise in groundwater level is accompanied by a displacement of soil air and a decrease in soil gas diffusivity. These changes will contribute to decreased O_2 concentration in the soil, increased denitrification activity and, possibly, increased N_2O production during nitrification. This in turn may contribute to increased N_2O concentrations in the soil (Fig. 1) and to increased N_2O fluxes from the soil (Fig. 2).

Concentration of N_2O in the soil and surface N_2O flux were weakly correlated (Fig. 2). This confirms the results of other studies (e.g. Benckiser, 1994; Clayton et al., 1994; Goodroad and Keeney, 1985). The weak correlation may be due to (i) a delay between N_2O production in the soil and emission from the soil surface, (ii) absorption and/or dissolution of N_2O in the soil (water), and (iii) rapid production of N_2O near the soil surface with rapid diffusion of N_2O out of the soil. Another factor may be the large spatial variability of N_2O fluxes (Velthof and Oenema, 1995a).

Generally, N_2O concentration increased with increasing soil depth. Similar steady-state concentration profiles were also found by Benckiser (1994). They demonstrate, in part, the importance of N_2O production in the subsoil. The topsoil is generally the most active site for N_2O production, especially after N fertilizer application (e.g. Clayton et al., 1994). This is because N fertilizer application directly increases NO_3^- and NH_4^+ contents in the top soil and potential nitrification (MacDuff and White, 1985) and denitrification rates (Velthof and Oenema, 1995b) are much larger in the topsoil than in the subsoil of grasslands. However, due to higher moisture and lower oxygen contents in the subsoil N_2O production can be much larger in the subsoil than in the topsoil, especially in peat soils with significant denitrification potential in the subsoils (Velthof and Oenema, 1995b).

Seasonal variations in N_2O losses

Seasonal variations in N_2O losses are mainly the result of variations in weather conditions and grassland management. Temperature and rainfall control rates of carbon (C) and nitrogen (N) mineralization (MacDuff and White, 1985), denitrification (Keeney et al., 1979) and nitrification (MacDuff and White, 1985), N uptake by the grass, groundwater level and gas diffusivity in soils. Besides application of N fertilizer and grazing, other management measures may also affect N_2O losses, e.g.

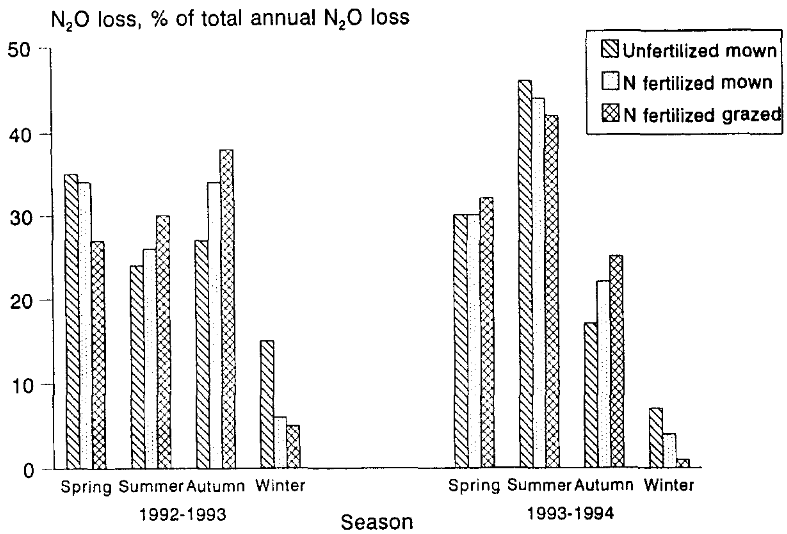

Figure 5. Relative N_2O losses in spring, summer, autumn, and winter in both years, as percentage of the total annual N_2O loss. Averages of all sites.

tractor wheels compact the soil during e.g. mowing and harvesting, which may enhance N_2O losses (Hansen and Bakken, 1993). Mowing itself may also increase N_2O flux (Beck and Christensen, 1987). After mowing, roots may release carbon compounds. Moreover, evapotranspiration and NO_3^- uptake by the sward may be decreased. All these temporal changes after mowing may enhance denitrification activity in the soil. In addition, irrigation, adjustment of groundwater level, liming and application of phosphate and other nutrients and chemicals may affect seasonal fluctuations in N_2O losses (Granli and Bøckman, 1994).

The seasonal patterns in mineral N contents of the unfertilized mown grassland (Fig. 3) are probably related to seasonal patterns in N mineralization rate, with highest rates during the growing season and lowest rate during the off-season (Gill et al., 1995). Similar seasonal patterns were found for N_2O losses (Figs. 3, 4 and Table 4). The much larger losses from peat soil II during winter, 0.8–1.6 kg N ha^{-1}, than from the other soils may have been due to higher mineralization rates and higher mineral N contents during winter in peat soil II than in the other soils.

In grazed grasslands, much N is accumulated in the soils via deposition of urine and dung from grazing cattle (Fig. 4). This N is vulnerable to loss via ammonia volatilization (Bussink, 1994), leaching (Ryden et al., 1984) and denitrification (Kirkham and Wilkins, 1993; Watson et al., 1992). The results of the present study showed that total N_2O losses were larger from grazed grasslands than from mown grasslands in spring, summer and autumn (Tables 2 and 4). In autumn, absolute and relative losses generally increased in the order: unfertilized mown < N-fertilized mown < N-fertilized grazed grassland. This order reflects the differences in the build-up of mineral N in the soil between different treatments (Fig. 4 and Table 3).

The small differences in N_2O loss between the treatments in the winter (Table 2) did not confirm our hypothesis that N_2O loss in the off-season increases in the order: unfertilized mown grassland < N-fertilized mown grassland < N-fertilized grazed grassland. At the end of the autumn, soil mineral N contents in the top soil had decreased to relatively low levels in all treatments (Fig. 4 and Table 3), probably because of leaching and denitrification after the heavy rainfall and groundwater level rise. As a consequence, residual effects of fertilizer N and N from dung and urine on N_2O losses were very small. Relative N_2O losses in the off-season were in the order: unfertilized mown > N-fertilized mown > N-fertilized grazed grassland (Fig. 5). These results clearly indicate that disregarding off-season losses underestimates the total from unfertilized mown grassland to a greater extent than those from N-fertilized mown and grazed grasslands.

Differences in seasonal N_2O losses between soil types were large. Relatively large losses occurred on the clay soil in spring (Table 2). By contrast, peat soil I exhibited relatively small losses in spring. So far, we have no clear explanation for these phenomena, but differences in rainfall patterns and groundwater level (Table 1) are probably involved.

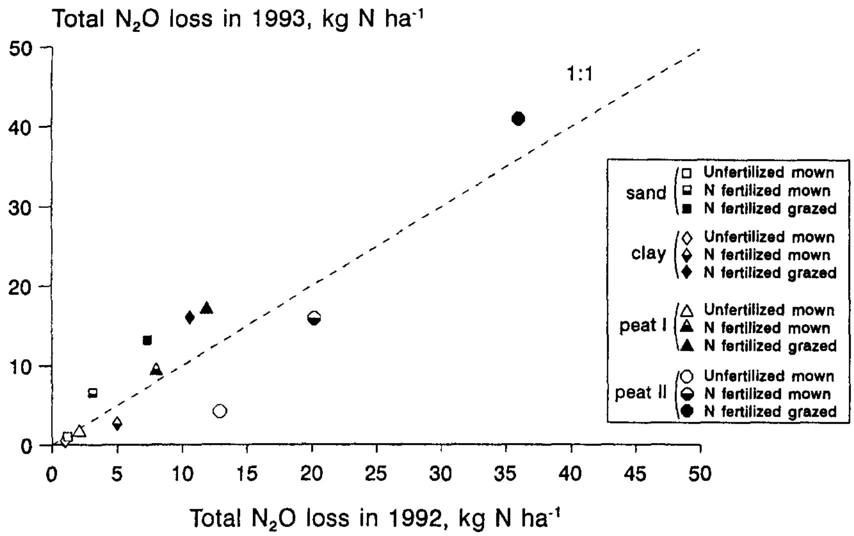

Figure 6. Total N_2O losses in 1992 (March 1992 – February 1993) versus total N_2O loss in 1993 (March 1993 – February 1994) for the four sites.

Interannual variations in N_2O losses

The larger N_2O losses from the unfertilized grasslands in the first year than in the second year of the experiment (Table 2 and Fig. 6), have to be attributed, in part, to the intensive grassland management in the year before the experiment started, with N applications via mineral N fertilizer in the range of 250–350 kg N ha^{-1} and 4 to 6 grazing cycles per year. This is supported indirectly by the higher mineral N contents in the unfertilized soil in the first year than in the second year (Fig. 3).

Interannual variations in N_2O losses from N-fertilized grasslands are confounded with interannual variations in e.g. N fertilizer application. The economically optimum fertilizer N input was considerably larger in the second year than in the first year (Table 4). This may have contributed to larger N_2O losses. Whilst many factors may have contributed to interannual variations, there is a fairly good linear relationship between N_2O losses in 1992–1993 and 1993–1994 (Fig. 6). This suggests that results of flux measurements carried out in one year have predictive power for estimating losses in other years.

Total annual N_2O losses

Using data from studies with a coverage of one year on cropped fields and ungrazed grasslands on mineral soils, Bouwman (1995) estimated total annual N_2O losses from agricultural land with the equation: N_2O loss = 1 + 0.0125(N application), in which N_2O loss and N application rate are given in kg N ha^{-1} yr^{-1}. The mean total N_2O loss for unfertilized and mown grassland on the sand and clay soils was 0.9 kg N ha^{-1} yr^{-1} and on average 0.95% of the fertilizer N applied was lost as N_2O on these soils (Table 4; n = 4). These results for mown grassland on sand and clay soils reasonably fit the regression equation of Bouwman (1995). Results for mown grassland on peat soils and all grazed grassland do not agree with the equation of Bouwman (1995).

The mean total N_2O loss from unfertilized mown grasslands on peat soils was 5.3 kg N ha^{-1} yr^{-1} and on average 3.0% of the fertilizer N applied to the peat soils was lost as N_2O (Table 4; n = 4). Hence, the average N_2O loss from mown and fertilized grasslands on peat soils is: N_2O loss = 5.3 + 0.03(N application), in which N_2O loss and N application rate are given in kg N ha^{-1} yr^{-1}. The differences between the peat soils were large and most probably related to differences in GWL, denitrification potential and contents of mineralizable carbon (Velthof and Oenema, 1995b).

The relationship between N_2O losses from mown grassland and those from grazed grassland on all soils in the present study was (Fig. 7): N_2O loss grazed grassland = 3.4 + 1.8(N_2O loss mown grassland). The much larger N_2O losses from grazed than from mown grasslands indicate that N_2O budget calculations for grasslands must include the effects of grazing and N cycling via urine and dung (Bouwman, 1995).

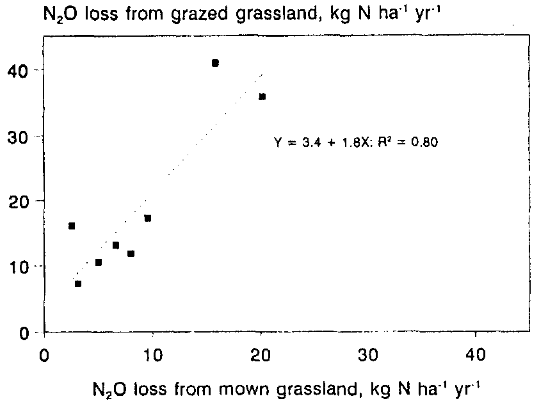

Figure 7. Relationship between N_2O loss from N-fertilized and mown grassland and that from N-fertilized and grazed grassland. Results for all sites and both years. Amount of applied N fertilizer was equal for mown and grazed grasslands.

The equations to estimate N_2O losses from managed grasslands on peat soils and from grazed grasslands may be considered as a rough approximation of N_2O losses from these grasslands. Their applicability to other peat soils and grazed grasslands are still unknown. More N_2O monitoring studies on grassland are needed to check and improve the equations for grassland on peat soils and for grazed grasslands.

Conclusions

Seasonal variations in N_2O losses from managed grasslands in The Netherlands were large and were related to fertilizer N application, grazing, weather conditions and changes in groundwater level. On all soils, largest N_2O losses occurred during the growing season. In late autumn, losses of N_2O tended to increase in the order: unfertilized mown < N-fertilized mown < N-fertilized grazed grassland, which reflected the build-up of mineral N in the soils. In winter the differences in both N_2O losses and mineral N contents were small between the management treatments. Disregarding off-season losses would underestimate total annual losses by up to 20%, total losses being largest for unfertilized mown grassland and the smallest for N-fertilized grazed grassland. Off-season losses from grassland on peat soil II were much larger than those from the other soils. This indicates that disregarding off-season N_2O losses will underestimate total annual losses from various sites in a different way.

Despite the considerable interannual variations in N_2O losses, this study indicates that the results of measurements carried out in one year have predictive power for estimating N_2O losses in other years. The interannual variations in N_2O losses in the present study and in studies of McTaggart et al. (1994) and Webster and Dowdell (1982) points to the present uncertainties in the estimates of total N_2O losses from agricultural land. Unless we are able to relate variations in N_2O losses between years to differences in N input, groundwater level, and weather conditions, errors in the estimates will remain, due to spatial and temporal variations. However, the effects of this random variation on the global budget calculations will attenuate if the number of monitoring studies increases.

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