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Nitrous oxide emissions from grazed grassland

O. Oenema[1], G.L. Velthof[2], S. Yamulki[3] & S.C. Jarvis[3]

Abstract. Grazing animals on managed pastures and rangelands have been identified recently as significant contributors to the global N_2O budget. This paper summarizes relevant literature data on N_2O emissions from dung, urine and grazed grassland, and provides an estimate of the contribution of grazing animals to the global N_2O budget.

The effects of grazing animals on N_2O emission are brought about by the concentration of herbage N in urine and dung patches, and by the compaction of the soil due to treading and trampling. The limited amount of experimental data indicates that 0.1 to 0.7% of the N in dung and 0.1 to 3.8% of the N in urine is emitted to the atmosphere as N_2O. There are no pertinent data about the effects of compaction by treading cattle on N_2O emission yet. Integral effects of grazing animals have been obtained by comparing grazed pastures with mown-only grassland. Grazing derived emissions, expressed as per cent of the amount of N excreted by grazing animals in dung and urine, range from 0.2 to 9.9%, with an overall mean of 2%. Using this emission factor and data statistics from FAO for numbers of animals, the global contribution of grazing animals was estimated at 1.55 Tg N_2O-N per year. This is slightly more than 10% of the global budget.

Keywords: Nitrous oxide, emission, grazing, grasslands

INTRODUCTION

The concentration of nitrous oxide (N_2O) in the atmosphere has been increasing at a rate of approximately 0.25% per year during the last decade (Prinn *et al.*, 1990; IPCC, 1994). This increase has been attributed to a number of factors, including changes in land use and increases in nitrogen fertilizer use and number of livestock (Khalil & Rasmussen, 1992). Thus far, terrestrial soils are thought to be the major sources of atmospheric N_2O, and changes in and on terrestrial soils are suggested to be the main cause of the increases in the concentration of atmospheric N_2O. In soils, N_2O is released during microbial transformations of nitrogen (N), i.e. nitrification, the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification, the reduction of NO_3^- to dinitrogen (N_2).

Approximately 20% of the earth's land surface is covered with managed pastures and another 30% with rangelands (Snaydon, 1981). These areas provide the staple food for numerous animals, notably ruminants. Grazing animals excrete much of the N that they consume in urine and dung, because the amount of N in the grass is generally much larger than the animals' requirements for amino acid and protein synthesis. This holds especially for intensively managed grasslands. On grazed grassland, grazing animals thus concentrate the N in dung and urine patches, which cover only a small fraction of the total surface area (Haynes & Williams, 1993). It has been known for some time that these patches are important sites for N loss via ammonia volatilization (Jarvis *et al.*, 1989), nitrate leaching (Ryden *et al.*, 1984), denitrification and N_2O emission (Ryden, 1986). Both the high N concentration, the form of the N compounds and the subsequent N transformations contribute to these high losses. The amount of N_2O emitted to the atmosphere is relatively small when expressed as a percentage of the amount of N in dung and urine patches. However, when expressed on a global basis, urine and dung patches are important sources of N_2O (Flessa *et al.*, 1996; IPCC, 1997).

There are additional effects brought about by grazing animals that may potentially enhance N_2O emissions from grassland. Treading and trampling by the animals lead to local compaction of the soil, especially in moist and wet conditions (Naeth *et al.*, 1990). Compaction decreases the total pore volume, especially the number of large pores. This in turn decreases the aeration of the soil, possibly leading to partial anaerobiosis and to changes in N transformation and N_2O production rates. Grazing animals may also alter species and herbage composition and the turnover of carbon (C) and N in stubble and roots; overgrazing may lead to erosion (Haynes & Williams, 1993). All these effects can potentially affect N_2O emissions from grassland.

The purpose of this study is to briefly review the effects of grazing animals on N_2O emissions from grassland, to identify the major controlling factors and, whenever possible, to quantify their effects on N_2O emission rate. Nitrogen forms and contents in dung and urine, and N_2O producing processes in dung and urine and their controlling factors are discussed first. A brief overview of literature data about N_2O from dung, urine and grazed grassland is presented thereafter, followed by an estimate of the total N_2O emission from

[1]Research Institute for Agrobiology and Soil Fertility (AB-DLO), P.O. Box 129, NL-9750 AC Haren, The Netherlands.
[2]NMI, Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, P.O. Box 8005, NL-6700 EC, Wageningen, The Netherlands.
[3]Institute of Grassland and Environmental Research (IGER), North Wyke Research Station, Okehampton, Devon, EX20 2SB, England, UK.

grazed grassland on a global scale. The last section deals with management options that minimize emissions from grazed grassland.

MAJOR FACTORS AND TRANSFORMATION PROCESSES

Nitrogen compounds in dung and urine

The retention of N in animal products, i.e. milk, meat and wool, ranges generally from 5 to 20% of the total N intake. The remainder is excreted via faeces and urine. Sheep have 70–75% and dairy cows 60–65% of their excreted N in urine, when grazing N-rich grass/clover pastures. The concentration of N in urine may vary from 1 to 20 g/l, because of large variations in the N content of the diet and in consumption of water. Typically, over 70% (range 50 to 90%) of the N in fresh urine is present as urea and the rest consists of amino acids and peptides (Haynes & Williams, 1993). The bulk of the N in fresh faeces is in organic form. About 20–25% of faecal N is water soluble, 15–25% is undigested dietary N and the remaining 50–65% is present in bacterial cells.

Combining the amounts of N in urine and dung patches with their respective average surface areas provides the N deposition rate per unit surface area. The surface area of cattle dung patches is about 0.05 m^2 and that of cattle and sheep urine patches (wetted area) about 0.4 and 0.03 m^2, respectively. Hence, the N deposition ranges from about 20 to 80 g/m^2 in urine patches and from about 50 to 200 g/m^2 in dung patches.

Nitrous oxide producing processes and controlling factors

Nitrification and denitrification are microbial processes capable of producing N_2O. In addition, there is evidence that some N_2O can be released through chemodenitrification (Tiedje, 1988), but this pathway is probably of minor importance in dung and urine patches. The organically bound N in urine and faeces must be first mineralized by heterotrophic organisms to NH_3/NH_4^+, before it becomes the substrate of nitrifying and, subsequently, denitrifying organisms. In urine patches, the hydrolysis of urea to NH_3/NH_4^+ is usually completed within one day (Ball & Ryden, 1984), whilst the mineralization of amino acids and peptides takes only a few days. In dung, the ammonification of the water soluble organic N compounds and a fraction of the organic N compounds from bacterial cells is also rapid, leading to a gradual increase in the amount of NH_3/NH_4^+. However, the remaining N is rather resistant and mineralization may take months or years. The ammonification is associated with an increase in pH because of the high pKa value (9.15) of the NH_3/NH_4^+ equilibrium. In urine patches, where urea is rapidly hydrolysed into NH_3/NH_4^+ and $CO_3^{2-}/HCO_3^-/CO_2$ species, the rise in pH is rapid and strong (Fig. 1).

The autotrophic nitrifiers oxidize the energy-rich NH_3/NH_4^+ to NO_2^- and subsequently to NO_3^-. Nitrifying organisms are relatively slow growing and it may take weeks before the 20 to 80 g/m^2 of ammoniacal N in urine patches has been nitrified completely. Because nitrite-oxidizing bacteria are more rapidly inhibited by NH_3 than ammonia-oxidizing bacteria, there can be a temporary accumulation of NO_2^- (Fig. 1) and an increased release of N_2O (Monaghan & Barraclough, 1993). The temporary accumulation of NO_2^- in urine patches

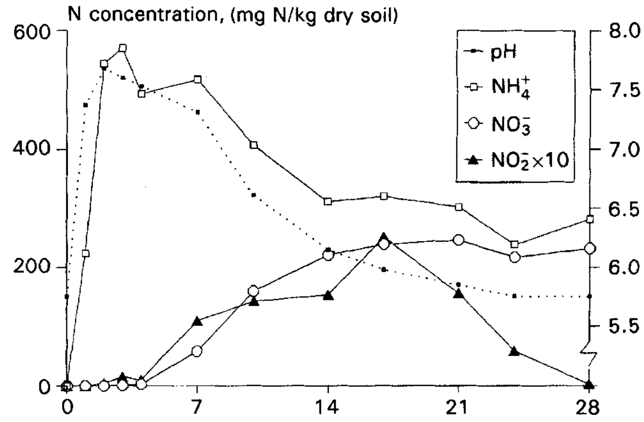

Fig. 1. Patterns of soil pH and concentrations of NH_4^+, NO_2^- and NO_3^- in a simulated urine patch (soil layer 0–5 cm); a total of 1.5 l solution with 10 g urea N/l was applied to grassland on day 0 (Velthof & Oenema, unpublished results).

is central to N_2O release during the nitrification process. A low O_2 partial pressure in the soil also promotes the accumulation of NO_2^- and the release of N_2O. These conditions may occur especially in moist and wet soils where the mineralization of the easily metabolizable substrates from urine can significantly deplete the O_2 partial pressure. Thus nitrification is potentially an important and long-lasting source of N_2O in urine patches. Similar conclusions may be drawn for dung patches, although the initial concentration of NH_3/NH_4^+ species is much lower than with urine. There are, however, large amounts of mineralizable organic N in dung which can result in N_2O release via nitrification over a long period.

The heterotrophic denitrifiers use NO_3^- and NO_2^- as electron acceptors, thereby reducing these oxidized N species to NO, N_2O and N_2. A number of factors may contribute to the temporary accumulation of the possible intermediates (Tiedje, 1988). The release of N_2O is relatively large when concentrations of NO_2^- and NO_3^- are high, soil pH is below 6 and small amounts of O_2 are present. In urine patches, large amounts of NO_3^- can be present following nitrification and, as nitrification is an acidifying process, the local decrease in soil pH from the initially high values resulting from ammonification to below 6 (Fig. 1), may enhance N_2O release from urine patches. The drop in pH may be especially large in soils with a low proton buffering capacity.

Nitrogen content as a major controlling factor of N_2O emission

Despite the many factors that control N_2O emissions at the process level, the relationship between N availability in the soil and N_2O emission appears to be the most useful thus far for evaluating the total emission from a certain area. The additional controlling factors can greatly enhance or decrease N_2O production rates, but their effects are very site-specific and quantitative information about environmental conditions is usually lacking, so at larger scales it is often simplest to consider N availability only.

The mean fraction of fertilizer N that escapes into the atmosphere as N_2O from fertilized grassland and arable land is estimated at 1.0–1.25% (Bouwman, 1995). For various reasons argued before, this percentage is suggested to be higher (up to 3.0%) for N from urine and dung, largely because of the elevated N concentrations in urine and dung patches.

There are indications that the relationship between N availability and N_2O emission may be curvilinear, with a progressive increase of N_2O emissions as N availability increases. Thus far there are only few data that may sustain the postulated curvilinear relationship between N availability and N_2O emissions (Harrison *et al.*, 1995; Velthof *et al.*, 1997).

NITROUS OXIDE EMISSION FROM DUNG, URINE AND GRAZED GRASSLAND

Nitrous oxide emissions from dung pats

Allen *et al.* (1996) have estimated that the total annual N_2O emission from dung pats in typical grazing pastures in England ranged from 53 to 1583 g N_2O N/ha per y, assuming a daily deposition per animal of 10 times 2 kg of dung, a stocking rate of 2 animals per ha and 180 grazing days per year. The wide range was related to variations induced by the time of deposition, weather conditions and soil type. Large fluxes were measured on a moderately well-drained soil and lower fluxes on a poorly-drained soil. By contrast, Yamulki *et al.* (1997) showed that fluxes from poorly drained soil were similar to those from moderately well-drained soil, and that emissions were larger from dung deposited in autumn (109 g N_2O N/ha per y) than from dung deposited in summer (24 g N_2O N/ha per y) (Fig. 2). It was suggested that moisture content was a major regulating factor. During sunny and dry weather, the early formation of a crust protects the dung pat and hinders its disintegration, whereas prolonged rainfall may leach soluble compounds and may erode the pat (*cf.* Marsh & Campling, 1970). Hence, environmental effects may greatly affect the physical properties and biogeochemical processes in the dung and influence N_2O emission. This can provide an additional explanation why fluxes from dung can vary greatly in time.

Table 1 summarizes results of experiments measuring N_2O from animal excrement and from grazed grassland. Results from Yamulki *et al.* (1997) show that in England the emission factor may range from 0.03% for dung applied in July to 0.74% for dung applied in October. Results from Germany and the Netherlands also fall within this wide range. We suggest that 0.4% is a reasonable overall mean emission factor, and by combining this percentage with the total amount of N in cattle dung pats (i.e. 50 to 200 g N/m^2), a total N_2O emission from dung pats in the range 0.2–0.8 g N/m^2 per y can be calculated.

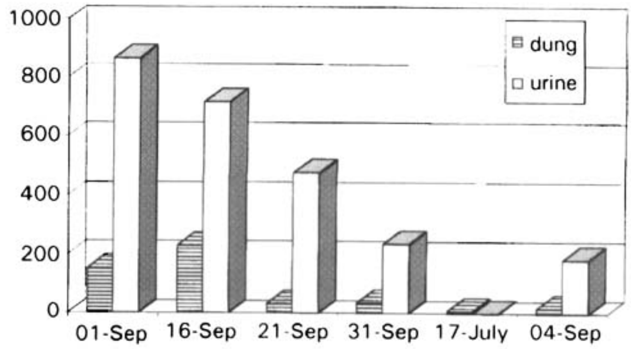

Fig. 2. Simulated annual emission from cattle dung and urine patches, following deposition of urine and dung at various dates across the season, based on a stocking rate of 2 animals per ha and 180 grazing days per year (after Yamulki & Jarvis, 1997).

Nitrous oxide emissions from urine patches

Inhibition of the nitrification process by adding a nitrification inhibitor greatly reduced the N_2O emission from urine (Williamson & Jarvis, 1997). This clearly indicates the importance of the nitrification process as the trigger for the release of N_2O from urine patches. Using specific inhibitors, Koops *et al.* (1997) showed that N_2O losses via nitrification accounted for 1.3% and via denitrification for 0.9% of the N from urine. Evidently, nitrification was the main source of N_2O from urine in this experiment on peat soil. The data suggest that nitrifier denitrification was important, but the available measuring techniques do not yet allow its quantification in the field.

Table 1. Emission of N_2O from animal dung and urine deposited on grassland; a compilation of published and unpublished data. The emitted amount of N_2O-N is expressed as a % of the amount of N excreted by the grazing animal

Country	Soil type	Treatment	Measurement period (days)	N_2O emission (%)	Reference
United Kingdom	clay loam	dung	66–417	0.1–0.7	Yamulki *et al.* (1997)
Germany	loess	dung	77	0.5	Flessa *et al.* (1996)
Germany	sand	dung	365	0.4	Poggemann *et al.* (1995)
The Netherlands	sand	dung	184	0.7	Velthof, unpublished data
USA	clay loam	urine	300	0.6	Mosier & Parton (1985)
United Kingdom	clay loam	urine	30	1.0–5.0	Monaghan & Barraclough (1993)
United Kingdom	clay loam	urine	60–417	0.1–1.4	Yamulki *et al.* (1997)
Belgium	sand loam	urine	19–35	0.1–2.4	Vermoesen *et al.* (1997)
New Zealand	silt loam	urine	100	1.0–3.0	Clough *et al.* (1996)
New Zealand	–	urine	42	< 0.5	Sherlock & Goh (1983)
Germany	loess	urine	77	3.8	Flessa *et al.* (1996)
The Netherlands	clay	urine	28	0.5	Velthof & Oenema (1994)
Germany	sand	urine	365	0.4–1.3	Poggemann *et al.* (1995)
United Kingdom	clay loam	grazing	7	8.0	Velthof *et al.* (1996a)
The Netherlands	sand+clay	grazing	224–730	1.0–3.3	Velthof *et al.* (1996c)
The Netherlands	peat	grazing	224–730	1.5–9.9	Velthof *et al.* (1996c)
New Zealand	silt loam	grazing	730	0.2–1.0†	Carran *et al.* (1995)

†These percentages were calculated on the basis of data presented by Carran *et al.* (1995) and additional assumptions.

Percentage losses as N_2O-N appear to be larger for urine than for dung (Table 1), probably as the result of the larger amounts of ammoniacal N. Variations in N_2O emission following urine application are wide and have been attributed to urine composition, soil type and environmental conditions during and after application (Sherlock & Goh, 1983; Monaghan & Barraclough, 1993; Allen *et al.*, 1996; Yamulki *et al.*, 1997; Müller *et al.*, 1997). Mosier & Parton (1985) observed that during the course of a year, 0.6% of the urea N from simulated urine patches was emitted as N_2O from semi-arid shortgrass prairie. About ten years later, they found that N_2O emissions remained detectably higher in the urine patch compared to the surrounding area (Mosier *et al.*, 1991), suggesting that measurements for one year underestimate the amount of N_2O emitted to the atmosphere. Emission factors range from less than 0.1 to 3.8%, with 1.5 as overall mean (Table 1). So far, the data do not allow us to conclude whether or not N_2O emissions are linearly or curvilinearly related to the N content of urine.

Nitrous oxide emission as a result of treading

Treading by grazing animals may compact the soil (Table 2). Many factors may affect the magnitude of compaction, like stocking rate, soil type, moisture content and size and type of animal (e.g Warren *et al.*, 1986;. Naeth *et al.*, 1990).

Soil compaction retards water infiltration and gas diffusivity, leading to, for example, a decreased O_2 concentration and more anaerobic sites in which N_2O is produced (Hansen & Bakken, 1993). Douglas & Crawford (1993) found that N_2O emissions and denitrification rates were up to 2 times larger in compacted soil than in uncompacted grassland soil. Torbert & Wood (1992) showed that total ^{15}N losses increased by a factor of 3.6 when bulk density of a loamy sand increased from 1.4 to 1.8 t/m^3 at 60% water-filled pore space. Denitrification was suggested to be the major cause of N loss. The study indicated that compaction is important in shifting soil conditions towards an anaerobic state at the same level of water-filled pore space.

To illustrate the potential scale of the effects of treading by cattle, we estimated that the potential compacted area is in the order of 100 m^2 per cow per day, by assuming a mean total surface area of the four hoofs of 500 cm^2, a mean step size of 0.5 m, and a mean walking distance of 2 km per cow per day. We note that the number of cow grazing days per ha per year may range from approximately 100 to as high as 700 on intensively managed grassland. Combining these data shows that the compacted surface area of the grassland would be 1 to 7 times the surface area of the grassland, if the coverage by hooves was evenly distributed. The coverage is, however, far from even; compaction by treading is much more severe in camping areas and cattle paths than in grazed-only areas. Camping areas also receive larger amounts of dung and urine, suggesting that these areas are hot spots for N_2O emissions. We suggest that treading by cattle may easily enhance N_2O emissions from grassland by a factor of two, as indicated by the few available data on the effects of compaction on N_2O in soil discussed before. Similar, but less severe, effects are to be expected from sheep grazing. Evidently, there is great need for quantifying the effect of treading on N_2O emission from grazed grassland and camping areas.

Table 2. Soil bulk density in t/m^3 of a clay loam soil in a long-term grazed fescue grassland in Alberta (Naeth *et al.*, 1990). Treatments with different letters in a column are significantly different ($P < 0.05$)

Grazing intensity	0–7.5 cm depth	15 cm depth
Very heavy	0.90a	0.70a
Heavy	0.83b	0.48bc
Moderate	0.80b	0.40c
Light	0.83b	0.58b
Control	0.75c	0.51b

Nitrous oxide emission from grazed grassland; integral effects

Grazed grassland can be seen as an aggregation of urine patches, dung patches, compacted footprints, camping sites, grazed-only areas and mixtures of these sites. Micrometeorological techniques are capable of integrating the surface flux from the various aggregate units, but are only now becoming available and are not applicable to all sites (Mosier, 1989). Properly placed flux chambers also provide reasonable accurate estimates of N_2O emissions from grazed grassland, and nearly all results given here are by the chamber method.

Results of a monitoring study comparing N_2O emissions from grazed and mown-only grassland on four different soil types for two consecutive years, clearly indicate the marked effects of grazing (Velthof & Oenema, 1995a, b; Velthof *et al.*, 1996c). Fluxes of N_2O were generally larger from grazed grasslands than from mown grasslands, especially during wet periods in autumn (Fig. 3). In winter, however, both soil mineral N contents and N_2O fluxes were similar in mown and grazed grassland. Annual N_2O losses from intensively managed grazed grasslands ranged from 10.3 kg N/ha per y on the sand to the high figure of 38.5 kg N/ha per y on peat soil II (Fig. 4).

Van Cleemput *et al.* (1994) showed that spatial variability of N_2O fluxes from grazed grassland was large on a small (1 m^2) and large scale (10 000 m^2), and at all scales fluxes were log-normally distributed. The small scale variability can be related to the generally patchy distribution of soil NO_3^- and NH_4^+ concentrations, bulk density, water-soluble C contents, and

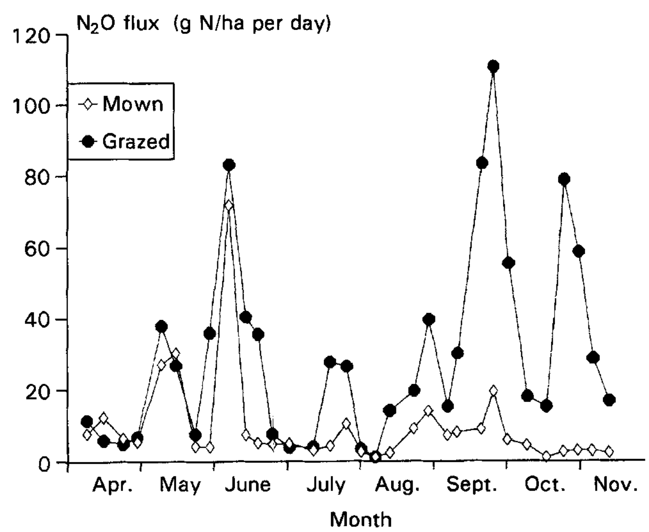

Fig. 3. Fluxes of N_2O from N fertilized-mown and N fertilized-grazed grassland on sand soil in the Netherlands during April–November 1993 (after Velthof & Oenema, 1995b).

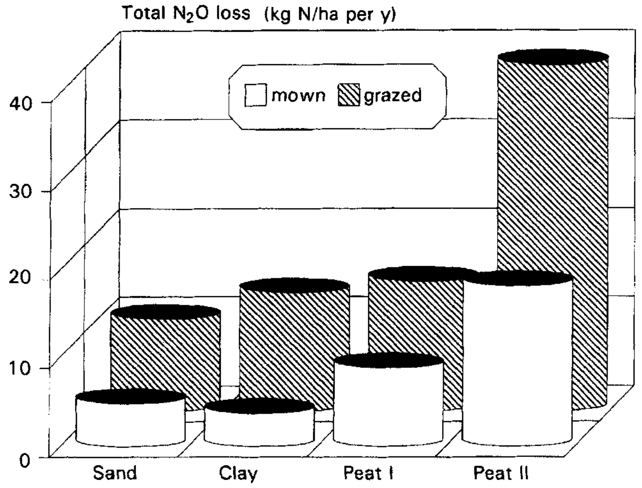

Fig. 4. Total annual N_2O losses from N fertilized-mown and N fertilized-grazed grasslands on a sand, a clay and two peat soils in the Netherlands (after Velthof *et al.*, 1996c).

of nitrification and denitrification rates (e.g. Fig. 5). Large scale variability can be related generally to grazing and camping patterns (e.g. Colbourn, 1993), and to heterogeneities in sward, soil and topography.

Evidently, grazing animals greatly increase total N_2O emissions. The grazing-derived emissions range from 0.2 to 9.9% of excreted N (Table 1). The lowest figure has been estimated from data of extensively managed sheep-grazed pastures in New Zealand (Carran *et al.*, 1995) and the highest figure is for intensively managed grassland on peat soils in the Netherlands. We suggest an overall mean grazing-derived emission of 2%, with a possible range of 0.5 to 3.0%, similar to IPCC guidelines (IPCC, 1997).

GRAZING ANIMALS AND GLOBAL NITROUS OXIDE EMISSIONS

On a global scale, grazing animals contribute about 1.55 Tg N_2O-N (IPCC, 1996), which is more than 10% of the total annual flux of 14 Tg N_2O-N into the atmosphere (e.g. Khalil & Rasmussen, 1992). This estimate is based on the number of animals per region, total N excretion per animal per year per region, the percentage of the urine and dung that is deposited on grassland, and a mean grazing derived emission factor of 2%, and includes all direct and indirect effects of the grazing animals on N_2O emission. Non-dairy cattle (including buffaloes) contribute 40%, dairy cattle 6%, sheep 21% and other animals (goats, horses, mules, donkeys and camels) 32% to the total emission of about 1.55 Tg per year (Table 3). There are small additional emissions of about 50 Gg N_2O-N from pigs and poultry excreta deposited on grassland and/or rangeland.

Background emissions from grassland, prairies and rangeland are not included in this estimate. Emissions from dung and urine deposited in housings which, after storage is applied to the soil, are also not included in Table 3: much of the animal slurries and manures is applied to arable land and not to grassland and rangeland.

The estimates presented in Table 3 agree reasonably well with the estimates of Flessa *et al.* (1996), who used a mean emission factor of 3% but slightly lower amounts of N excretion per animal. Evidently, Table 3 clearly suggests that significant sources of N_2O occur in Africa, Asia and Latin America. Experimental evidence to sustain this suggestion is lacking, simply because there are very few or no measurements carried out in these regions. Nearly all measurements have been carried out in Western Europe, Oceania (New Zealand) and North America, regions that all together contribute only about 20% of the total estimated emission of 1.55 Tg/y.

MANAGEMENT OPTIONS TO MITIGATE N_2O EMISSIONS FROM GRAZED GRASSLAND

An overall decrease in N input to the farming system, whilst maintaining productivity by increased efficiency of N use, will result in a decrease in all N emissions, including N_2O. Further, there are three specific options to lower N_2O emission from grassland, namely (i) increasing the productivity per animal concomitant with a decrease in animal numbers, (ii) lowering the N content of urine, and (iii) restricted grazing, i.e. decreasing the number of urine and dung patches.

Table 3. Estimated total N_2O emission from urine and dung deposited by animals during grazing. Number of animals per region were based on FAO statistics of 1990, as categorized by Shafley *et al.* (1992). Amount of N excreted per animal per year was based on IPCC (1997)

Region	Type of animal†	Number of animals ($\times 10^9$)	N excretion (kg per head per year)	N excretion (% on grassland)	N_2O emission (Gg per year)
Globe	Non-dairy cattle	1175.9	40–70	0–96	630
	Dairy cattle	227.5	60–100	13–100	92
	Sheep	1208.8	12–20	73–100	328
	Other	671.5	25–40	92–100	503
TOTAL					1553
Africa					292
N. America					123
S. America					320
Asia & Far East					378
E. Europe					64
W. Europe					79
Oceania					133
Near East & Mediterranean					164
TOTAL					1553

†The category 'Non-dairy cattle' also includes buffaloes; the category 'other' includes goats, horses, mules, donkeys and camels.

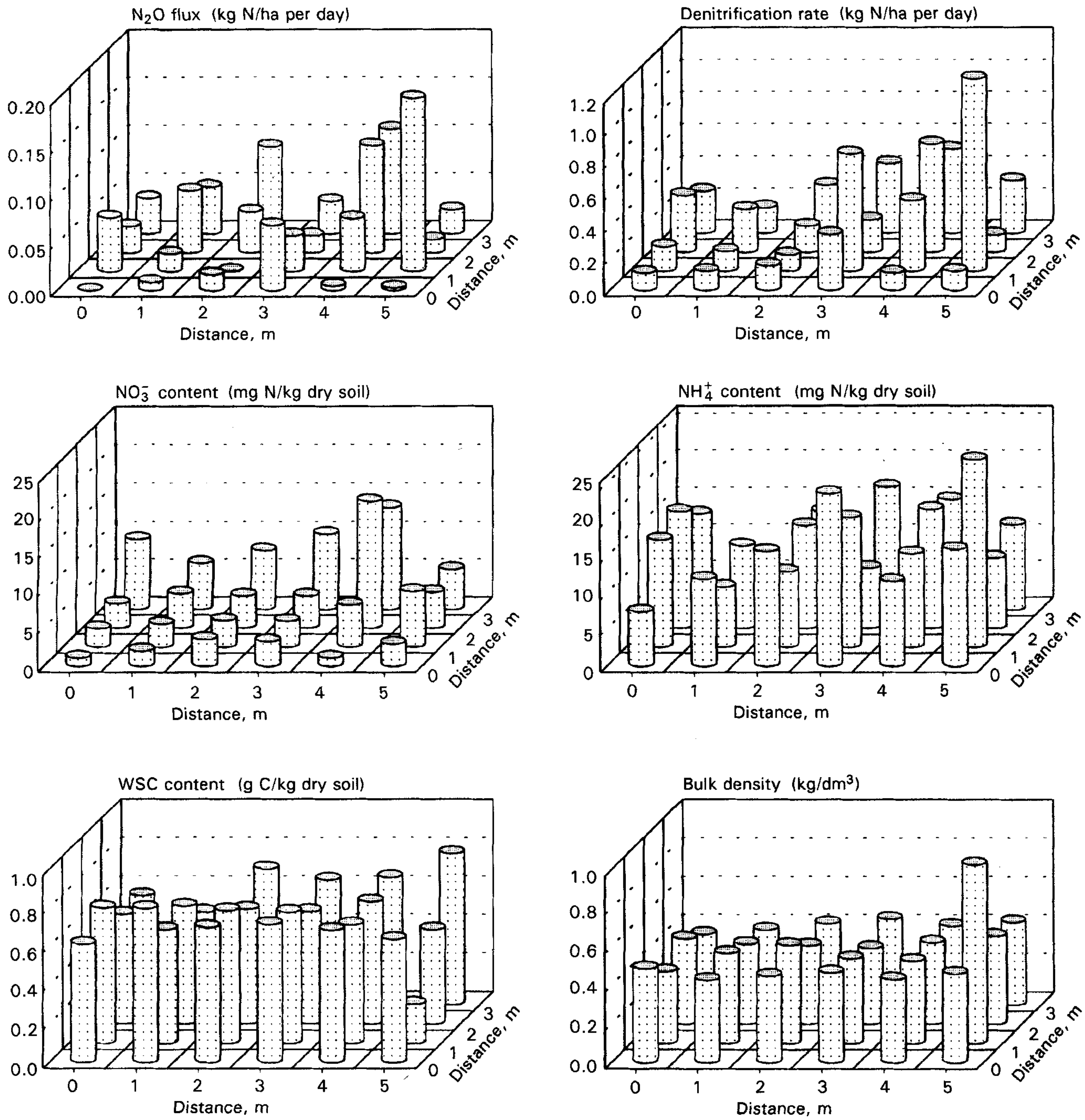

Fig. 5. Spatial patterns of N_2O fluxes, denitrification rates, NO_3^- and NH_4^+ concentrations, bulk density and water-soluble C (WSC) in grazed grassland on peat soil in the Netherlands in November 1993 (Velthof & Oenema, unpublished results). Multiple regression analyses indicated that NH_4^+ and NO_3^- contents were the major soil variables controlling N_2O fluxes, suggesting that both nitrification and denitrification were sources of N_2O (Velthof *et al.*, 1996b).

Simultaneously implementing these three options will yield the greatest decrease, but all three options can be implemented singly as well. Exploitation of the full potential of these options requires a thorough understanding of the N cycle of grazed grassland with its interactions, and a systems analysis approach. Such an approach may also circumvent the possibility that lowering N_2O emission increases other unwanted emissions.

The possible decrease in the size of the herd will more than outweigh the higher N_2O emission per animal head, when a low productivity herd is replaced by a high productivity herd, while the total milk, meat and or wool production remains the same, i.e. a substantial decrease in N_2O per unit product. This option can have a large beneficial effect, especially for extensively managed grazed grasslands, but it may take decades before the full potential can be realized, because animal breeding programmes and implementation of improved animal husbandry in practice all over the globe require long-term efforts.

Strategies that lower the N content of the urine include supplemental feeding of low-N fodders like maize, reducing the amount of N fertilizer applied, and delaying grazing in order to offer animals herbage with a low N content. In fact, all strategies that lower the total N intake of the animal but maintain the nutritional value of the feed will lower the N excretion of the animal and thereby the N_2O emission per animal head. This option is most relevant for the intensively managed grassland in for example, western Europe, where the mean N content of the fodder is often more than 30 g N per kg dry matter.

Restricted grazing is a possible option for the intensively managed grasslands in temperate areas only. It requires housing, appropriate slurry storage basins and slurry application techniques, and indoor feeding. The beneficial effect of this option is based on the fact that N_2O emissions, expressed as unit N_2O per unit N, are much higher from urine and dung patches than from slurry which has been applied to soil properly.

Little effort has been made so far to quantitatively evaluate the effects of the three specific management options, but the potentials are large. For example, it has been estimated that the total N_2O emission from dairy farming systems on sandy soil in the Netherlands can be reduced from 15.4 ± 9.4 kg N_2O N/ha per y to 5.2 ± 2.6 kg N_2O N/ha per y via improvement of the nutrient management, i.e. more productive herds, less N fertilizer application, supplemental feeding, and restricted grazing (Velthof & Oenema, in prep.).

CONCLUSIONS

Excreta from grazing animals have only very recently been identified as a major source of N_2O. Results thus far indicate that grazing animals contribute slightly more than 10% (i.e. 1.55 Tg N_2O-N) to the global annual N_2O budget.

The mechanisms of N_2O production in grazed grassland are reasonably well known, but the process rates and variables are poorly quantified. As a consequence, quantitative estimates of emission factors and N_2O budgets for grazed grassland in the various regions of the world have a wide confidence interval. The spatial distribution of measurements over the globe is also very uneven.

The effect of grazing animals on N_2O emission are predominantly brought about by two factors, namely the high N concentration in urine and dung which are unevenly distributed over the grassland, and compaction of the soil by treading. The first factor has received some attention, the second has not.

Specific management options to lower N_2O emissions from grazed grassland include (i) decreasing the number of grazing animals, (ii) decreasing the N content of urine, and (iii) decreasing the number of urine and dung patches. In practice and whilst sustaining the same level of productivity, this could be achieved by increasing productivity per cow, supplemental feeding of low-N fodders, delayed grazing, less N fertilizer application, and restricted grazing.

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