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Trends in global nitrous oxide emissions from animal production systems

Oene Oenema[1,2,*], Nicole Wrage[2,3], Gerard L. Velthof[1], Jan Willem van Groenigen[1], Jan Dolfing[1] and Peter J. Kuikman[1]

*[1]Wageningen University and Research Centre, Alterra, P.O. Box 47, 6700 AA Wageningen, The Netherlands; [2]Department of Soil Quality, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands; [3]Imperial College, Wye Campus Wye, Ashford, Kent TN25 5AH, UK; *Author for correspondence (tel: +31-317-474613; fax: +31-317-419000; e-mail: Oene.Oenema@wur.nl)*

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Abstract

Wastes from animal production systems contribute as much as 30–50% to the global N_2O emissions from agriculture, but relatively little attention has been given on improving the accuracy of the estimates and on developing mitigation options. This paper discusses trends and uncertainties in global N_2O emission from animal waste and discusses possible mitigation strategies, on the basis of literature data and results of simple calculations. Total N_2O emissions from animal production systems are estimated at 1.5 Tg. Dung and urine from grazing animals deposited in pastures (41%), indirect sources (27%), animal wastes in stables and storages (19%), application of animal wastes to land (10%) and burning of dung (3%) are the five sources distinguished. Most sensitive factors are N excretion per animal head, the emission factor for grazing animals and that for indirect emissions. Total N_2O emissions are related to type and number of animals, N excretion per animal, and the management of animal wastes. Projections by FAO suggest that animal numbers will increase by 40% between 2000 and 2030. Mean N excretion per animal head will probably also increase. These trends combined suggest a strong increase in total N_2O emission from animal production systems in the near future, which is opposite to the objectives of the Kyoto Protocol. Improving N use efficiency, combined with anaerobic digestion of animal wastes for bio fuel generation are the most feasible options for mitigation, but these options seem insufficient to reverse the trend of increasing N_2O emission. In conclusion, animal production systems are a major and increasing source of N_2O in agriculture. The uncertainties in the emission estimates are large, due to the many complexities involved and the lack of accurate data, especially about N excretion and the management of animal wastes in practice. Suggestions are made how to increase the accuracy of the emission estimates and to mitigate N_2O emission from animal production systems.

Introduction

Over the last few decades, the number of domestic animals in the world increased faster than the human population. Between 1960 and 2000, the human population roughly doubled, while the number of domestic animals tripled (FAO 2003). This relative increase in number of domestic animals reflects an increase in the consumption of animal protein per capita. In affluent countries, per capita animal protein consumption steadily increased throughout the last century, as diets change when incomes rise (e.g., Smil 2002). Similar changes occur in the developing countries; over the last four decades per capita meat consumption in the developing countries rose by 150% and that of dairy products by 60%. By 2030, per capita consumption of animal protein may well have increased by another 44% (Bruinsma 2003). As in the recent past, poultry consumption is expected to grow fastest. Between 1960 and 2000, the number of chicken increased by 281%, that of pigs by 124%, goats by 107% cattle by 43%, and sheep by 5% (Table 1; FAO 2003).

The feeding of this increased number of animals has been made possible in part through (i) the availability of N fertilizers, which has boosted crop production, and (ii) transport facilities, which allowed the physical separation of crop and animal production, and has contributed to improving the efficiency of converting animal feed into animal products. Currently, many intensive animal farms are specialized confined animal feeding operations (CAFO), which rely on the import of animal feed from elsewhere. In CAFOs, the available land is insufficient to provide feed for the animals and to recycle the nutrients contained in animal waste in an environmentally benign manner (Sims et al. 2004). Frequently observed ecological and societal impacts of CAFOs include pollution of air and water by nutrients, and problems with odour, animal diseases, animal welfare and food quality (e.g., Thompson and Nardone 1999). Such implications provide feedbacks to the management of CAFOs and also influence consumer behaviour, suggesting in part that future forecasts of per capita animal protein consumption and of animal number are somewhat uncertain.

Animal production systems have a relatively large share in the emissions of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) into the atmosphere (IPCC 1995; Bouwman et al. 1997; Oenema et al. 2001). The source of the gaseous nitrogen (N) emissions is the urine and dung excreted by the animals, either in pastures or in confinements (stables, barns, sheds, corrals). In the 1990s, animal agriculture emitted 22–32 Tg NH_3–N per year into the atmosphere, which translates to about 50–75% of the total anthropogenic NH_3 emissions (Bouwman et al. 1997). Annual emissions of N_2O from animal production systems and animal waste have been estimated at 2.7 Tg N (range 0.7–4.2), which translate to 30–50% of the total N_2O emission from agriculture (Mosier et al. 1998). However, these estimates are uncertain, especially for N_2O.

This paper focuses on trends and uncertainties in global N_2O emissions from the wastes from animal production systems. We discuss the possibilities for animal production systems to achieve the long-term objectives of the Kyoto Protocol to decrease the emissions by 50–60% by 2030 relative to the 1990s. Though the global amount of N in animal waste is at least as large the global total amount of N in N fertilizer consumption (70–90 Tg N per year; Fixen and West 2002), and the N_2O emission per unit of N from animal waste is at least as large as that of N fertilizer (Mosier et al.

Table 1. Forty-year trend in animal number in the world (FAOSTAT 2003).

Animal species	Animal number (millions)					Relative increase 1961–2000 (%)
	1961	1970	1980	1990	2000	
Cattle	942	1082	1216	1297	1343	43
Buffaloes	89	107	122	148	164	86
Sheep	994	1061	1096	1206	1047	5
Goats	349	376	462	585	722	107
Pigs	406	547	798	857	909	124
Chickens	3891	5216	7214	10680	14835	281
Ducks	193	256	352	553	969	401
Geese	4	55	69	132	234	6291
Turkeys	131	100	201	243	246	88
Horses	62	61	59	60	57	−9
Asses	37	39	38	43	41	10
Mules	10	12	13	15	13	26
Camels	13	16	17	19	19	47
Rabbits	101	137	194	387	496	391

1998), there has been less attention on animal waste than on N fertilizer by the research community. As a result, there are still few data to rely on. In this paper, we briefly review the available literature and make simple calculations and sensitivity analyses to reveal uncertainties in global N_2O emission from animal wastes and their management. To avoid an impression of unwarranted accuracy, estimates of N_2O emission from animal production systems are presented here in ranges rather than as single values.

Nitrogen cycling and N_2O production

Animal production systems transform animal feed (carbohydrates, protein) into milk, meat and eggs, and into dung and urine. Only a small fraction (5–30%) of the N in animal feed is retained in milk, meat and eggs, depending on animal type and management. The greater part (70–95%) is voided by the animals via urine and dung. In land-based or mixed animal systems, most of the N in the animal manure (50–90%) is returned to the land that produced the animal feed (Figure 1a), the remainder is lost during storage via NH_3 volatilization, denitrification and leaching and run off. In intensive animal production systems, like many CAFOs, the manure is disposed of off farm (Figure 1b), as the land-base is missing. The manure is either transported to land of other farmers, processed and composted, or treated as waste and discharged of or dumped. In some countries the dung is dried and used as bio fuel or as building material for houses.

The management and fate of the animal manure determines the emission of N_2O from animal

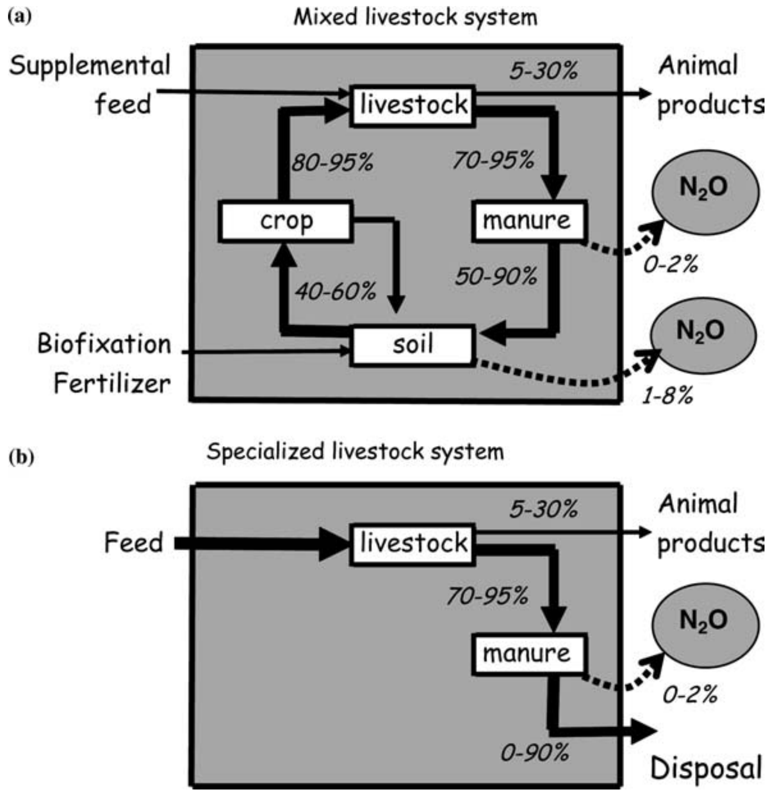

Figure 1. Nitrogen cycling in mixed animal production systems (a) and specialized animal production systems (b). Arrows indicate the relative size and direction of the N flows. Percentages indicate the estimated transfer of N from one compartment to the other compartment via animal feed and manure. Nitrous oxide (N_2O) is emitted from animal storages and soil. Losses of N other than N_2O have not been indicated. Note that N_2O emissions following disposal of manure in specialized animal production systems (b) have not been included (see text).

production systems. Most of the N_2O originates from microbiological transformations of N in the animal excrements urine and dung during storage and management and following application or deposition to land. Nitrifiers and denitrifiers are the principal producers of the gas (Granli and Bøckman 1994). Nitrifying microorganisms produce N_2O by nitrification and by nitrifier denitrification (Figure 2). In nitrification, N_2O develops during the oxidation of hydroxylamine (NH_2OH). In nitrifier denitrification, nitrifiers reduce nitrite (NO_2^-) via N_2O to dinitrogen (N_2). Not much is known about this latter pathway yet (Wrage et al. 2001). It is supposed to be similar to denitrification, where nitrate (NO_3^-) and NO_2^- are reduced via nitric oxide (NO) and N_2O to N_2 (Figure 2). It could be a significant source in animal production systems, as animal production systems create lots of opportunities for partial anaerobiosis, which is suggested to favour nitrifier denitrification and denitrification processes. In denitrification, N_2O is an intermediate, which may escape when the rate of N_2O production and the rate of N_2O consumption differ. The amount of N_2O released from denitrification depends on the absence of molecular O_2 and the presence of NO_3^- and metabolizable organic carbon. In addition to these microbiological sources, N_2O can be formed chemically in reactions involving NO_2^- (which is first produced biologically) under acidic conditions. This process is also called 'chemodenitrification', and some studies have shown this to be a predominant source of N_2O under specific conditions (e.g. Venterea and Rolston 2002). Because of this multitude of sources and environmental controls, which are only partly manageable, N_2O emissions from animal production systems have a highly stochastic nature.

Estimating N_2O emissions

The poor availability and quality of data and also the poor methodology for up-scaling and calculating aerial estimates (e.g., Van Aardenne 2002), results in uncertainty about the size of N_2O emissions. A wide range of animal production systems exists, and the management of these systems varies from farm to farm. In fact, we know surprisingly little about how farmers actually manage the storage and utilization of animal excrements, and how this management translates into emissions of N_2O into the atmosphere.

The IPCC Guidelines (IPCC/OECD/IEA 1997) provide a transparent methodology and guide to the preparation of greenhouse gas emission inventories, which we follow in this paper albeit with modifications and additional analyses. Animal production systems are grouped into types of Animal Waste Management Systems ($AWMS_T$), with different mean N_2O emission factors, reflecting the dominant influence of the management of animal excrements on N_2O emissions. The IPCC methodology for estimating N_2O emission from

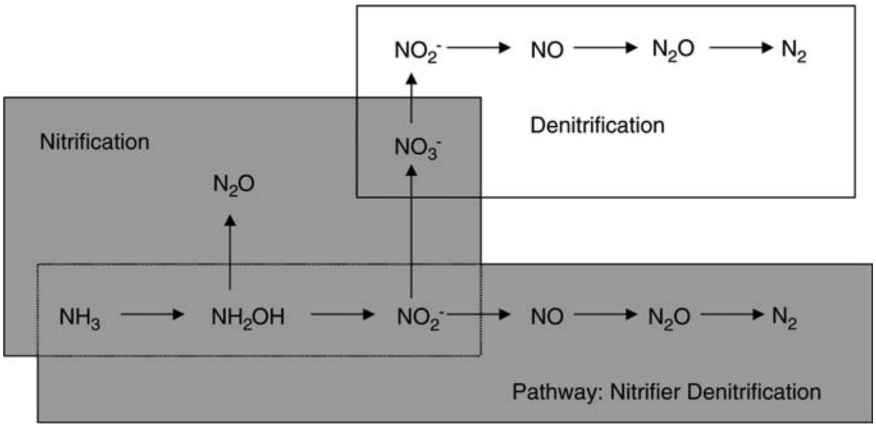

Figure 2. Biological transformations of N that lead to the formation of nitrous oxide (N_2O): nitrification, denitrification and nitrifier denitrification (from Wrage et al. 2001). Nitrifier denitrification is a pathway of nitrification.

these systems involves 7 steps to be carried out for each region distinguished, viz.,

1. Characterization of animal and poultry population ($N_{(T)}$ = number of animals of type T);
2. Determination of the mean annual N excretion ($Nex_{(T)}$) per animal for each animal category;
3. Determination of the amount of animal waste N in the various types of AWMS's ($AWMS_{(T)}$);
4. Correction of the amount of N in the AWMS's for possible N losses via NH_3 volatilization;
5. Application of the proper emission factor to each AWMS ($EF_{(AWMS)}$, in kg N_2O–N per kg of Nex in $AWMS_T$);
6. Calculation of N_2O emissions from: $N_2O_{(AWMS)} = \sum_{(T)}[N_{(T)} \cdot Nex_{(T)}\ AWMS_{(T)} \cdot EF_{(AWMS)}]$; and
7. Calculation of N_2O released following the application of the animal waste from AWMS's to land, according to $N_2O_{(\text{applied waste})} = N_{(\text{applied waste})} \cdot {}^{x}EF_{(\text{applied waste})}$.

The sensitivity of N excretion ($Nex_{(T)}$) and emission factors ($EF_{(AWMS)}$) on the estimated total N_2O emissions were estimated by analyzing the effects of possible variations in $Nex_{(T)}$ and $EF_{(AWMS)}$ by a factor 2 and 3, respectively. These factors were chose quite arbitrarily, but roughly reflect the size of the uncertainties in $Nex_{(T)}$ and $EF_{(AWMS)}$ (see below). This simple analysis allows the identification of the major sources of uncertainties in the estimated total N_2O emissions.

Animal number and N excretion

The number of all animal species increased between 1961 and 2000, except for horses (Table 1). Nearly exponential increases are observed for poultry and rodents, while increases for most other species tend to level off. Forecasts by FAO suggest further increases in animal number in the range of 30 to 50%, with largest increases for poultry (Bruinsma 2003). Increases will be relatively large in the developing countries while a (further) decrease is anticipated in some affluent countries, in response to globalization of markets and to societal concerns about animal welfare and environmental burdens of intensively managed confined animal feeding operations (CAFOs).

Estimates for the global total amount of N excreted differ almost by a factor 2. Smil (1999) arrived at an estimate of 75 Tg N per year (range 70–80) for the mid 1990s. Based on data presented by Bouwman et al. (1997), we calculate a total N excretion of 102 Tg for 1990, while Mosier et al. (1998) arrived at an estimate of 138 Tg for 1990. Differences between these estimates are related to differences in animal categorization and (mainly) N excretion per animal species (Table 2). Differences in N excretion per animal type are especially large for cattle, poultry, pigs, sheep and goats. N excretion depends on breed, age, weight, health, production level, and feeding of the animals. This holds especially for dairy cattle, as mean milk production per dairy cow may differ by more than a factor 4 and weight of the cows by more than a factor 2. As shown in Figure 3, N excretion by dairy cows increases nearly linearly with milk production and protein content (N content) of the animal feed. At a milk production per cow in the range of 1000–3000 kg per year and a protein content of the animal feed in the range of 10 and 15%, as in many developing countries, annual N excretion ranges between 30 and 60 kg per dairy cow. For

Table 2. N excretion per animal species, as listed by Bouwman et al. (1997), Smil (1999) and Mosier et al. (1998), in kg N per head per year, for developed countries (region I, modern) and developing countries (region II, traditional).

Animal species	Bouwman et al. (1997)		Smil (1999)		Mosier et al. (1998)	
	Region I	Region II	Modern	Traditional	Region I	Region II
Dairy cattle	80	60	80	45	70–100	60–70
Non-dairy cattle	45	40	50	30	60–70	40–50
Buffalo	45	45	30	30	40	40
Camels	55	55	35	35	40	40
Horses	45	45	35	35	40	40
Sheep	10	10	5	5	16–20	12
Goats	9	9	5	5	16–20	12
Pigs	11	11	10	10	16–20	16
Poultry	0.5	0.5	0.3	0.3	0.6	0.6

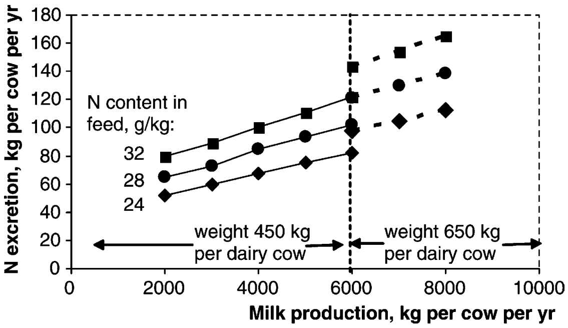

Figure 3. Calculated relationships between N excretion per dairy cow and milk production, animal weight, and mean N content of the animal feed. Note that the data for small dairy cows (body weight 450 kg) hold for milk production levels of 2000–6000 kg per cow, and those for large dairy cows (body weight 650 kg) for milk production levels of 6000 kg and more.

Table 3. Estimated total N excretion per animal species per region in 1990, in Tg N per year (after Bouwman et al. 1997).

Animal species	Region I	Region II	Total
Dairy cattle	8	8	16
Non-dairy cattle	13	31	44
Buffalo	0	6	6
Camels	0	1	1
Horses	1	2	3
Sheep	5	7	12
Goats	0	5	5
Pigs	4	6	9
Poultry	2	3	5
Total	33	69	102

high producing dairy cows in New Zealand, Western Europe and Northern America, milk production ranges between 5000 and 10,000 kg per head per year and the protein content of the animal feed ranges between 15 and 20%. This translates into an annual N excretion of 100–160 kg per dairy cow, i.e. 3 times as high as the average for developing countries. At similar production levels, variations in protein consumption may cause annual N excretion per head of cattle to vary by a factor of roughly 2. Such large differences indicate that detailed regional differentiation in N excretion according to production level and animal ration will improve the accuracy of global N excretion estimates.

Two-third of the global N excretion by animals is voided in developing countries (Asia, Latin America, Africa and Oceania, excluding Australia and New Zealand,) and one-third in developed countries. Cattle account for almost 60% of the total N excretion (Table 3). Non-dairy cattle (43%) are the single largest source, followed by dairy cattle (15%), sheep (12%) and pigs (9%).

Approximately 40–50% of total N excretion is collected in barns, stables, sheds and corals, while the remainder is voided in pastures. Both fractions are subjected to N losses via NH_3 volatilization. Further N losses may occur during burning of dung and during storage, composting and handling, and following application of animal waste to land. Estimates of the amounts of N from animal wastes applied to land differ almost a factor 3. Smil (1999) arrived at an estimate of 18 Tg N (24% of total N excretion), while Mosier et al. (1998) estimated that 49.7 Tg N (36% of total N excretion) was applied to land. When corrected for NH_3 volatilization, the net N loading of arable land via animal waste is estimated to range between 14 and 40 Tg per year (i.e., only 20–30% of total N excretion).

The projected increases in animal numbers until 2030 increase the need for animal feed. As there is no large expansion of the areas of agricultural land and grazing land possible, most of the additional feed has to come from increased crop production per unit area (Bruinsma 2003). Bouwman et al. (2003) estimated that the productivity of grassland has to increase by 39% to feed the increased number of ruminants. This increase will have to come from increasing inputs of fertilizers, grass-clover mixtures and improved management. In addition, vast increases in the productivity of arable land are needed to supplement the forage for ruminants and to feed the increasing number of poultry and pigs. Again, these increases will have to come from increasing inputs of fertilizers and improved management. Increasing inputs of N fertilizers and introducing more grass-clover mixtures will increase the protein content of the animal feed and the N excretion per animal head (e.g., Whitehead 2000).

Nitrous oxide emission factors for animal waste management

Nitrous oxide emitted from animal production systems is mainly produced from the N in animal waste (Figure 1). Four direct sources can be distinguished:

- urine and dung from grazing animals in pastures;

- dung collected from pastures and paddocks for use as bio fuel;
- animal wastes from (temporarily) confined animals during storage and handling; and
- animal wastes from (temporarily) confined animals following application to land. In addition, there are indirect sources associated with N lost from animal wastes that enters other systems and is there subject to N_2O producing processes (Mosier et al. 1998).

Table 4 presents an overview of the current default IPCC emission factors for animal waste management systems. Mean emission factors used in the current study are similar to the default IPCC emission factors except for a few, based on the analysis given below.

Emissions from urine and dung deposited by grazing animals in pastures

Between 40 and 60% of the total amount of N excreted is voided in pastures, covering roughly 7% of the Earth's surface, which is twice the area of arable land (3%). The amount of N_2O emitted from dung and urine in pastures varies greatly, mainly due to variations in soil and environmental conditions. Recent reviews suggest that the amounts of N_2O emitted range from 1 to 80 g per kg of N in excrements (Oenema et al. 1997, 2001). Emissions tend to be higher from intensively managed pastures compared to unmanaged pastures, and from imperfectly drained soils compared to well-drained soils. In New Zealand, emission factors for N excreted during grazing differ by a factor 5 for different soil drainage classes; i.e. 5 g for freely drained soils, 20 g for imperfectly drained soils, and 26 g per kg N for poorly drained soils (De Klein et al. 2003). Similarly, Velthof et al. (1996) found much higher emissions from intensively managed pastures on poorly drained peat soils than from similarly managed pastures on well-drained clay and sand soils.

The relatively high IPCC default emission factor for N from grazing animals (20 g per kg as compared to 12.5 g per kg for N from N fertilizer) has been justified on the grounds of the localized deposition of high amounts of both N and C in dung and urine, and associated effects of trampling and compaction by grazing animals. Freshly excreted urine and dung contain energy-rich and chemically reduced C and N compounds, which provide substrates for consortia of autotrophic and heterotrophic bacteria. As a consequence, temporary changes in pH, partial pressures of O_2 and NH_3, and in the concentrations of NH_4^+, NO_2^-, and NO_3^- occur in dung and urine patches, which are conducive to the release of N_2O (and nitric oxide, NO). Van Groenigen et al. (2004) reported a five-fold increase in urine-N emission factors after compaction, and an eight-fold increase after application of dung. Although such transformations can be simulated under controlled conditions (e.g., Jarvis and Pain 1997, and references therein), it is still a great challenge to extrapolate the information from these experiments, and thereby to improve the estimated N_2O emission from global pastures.

Uncertainty in the IPCC default emission factor for grazing animals is partly to the bias in research sites. Most of the measurements have been carried out in (intensively) managed pastures in temperate areas and not in the (extensively, unmanaged)

Table 4. Emission factors for N_2O from animal wastes according to the Revised 1996 IPCC Guidelines (IPCC/OECD/IEA 1997) and the means used in the current study.

Source of N_2O ($AWMS_{(T)}$)	Emission factor (g N_2O–N kg per N)		
	Revised IPCC 1996 Guidelines	This study	
		Region I	Region II
Dung and urine in pasture and paddocks	20	20	10
Anaerobic lagoons and liquid systems	1	1	1
Solid storage and dry lots	20	20	20
Dried dung used as bio fuel	7	7	
Other systems	5	n.a.	n.a.
Manure applied to land	12.5	6	6
Indirect sources	10–25	10	10

pastures in tropical areas, where most ruminants graze. The poorer feeds for cattle, sheep and goats obtained from pastures and road sides on freely drained soils would suggest that the mean N_2O emission from grazing animals is less for the tropics than for temperate areas, though differences in temperature may partly compensate for this suggested difference. We used a default emission factor of 10 g per kg N for developing countries (mostly in drier areas) and 20 g per kg N for affluent countries (mostly in temperate areas).

Emissions following burning of dung collected from pastures and paddocks

A large share of cattle waste in the Indian continent is gathered for fuel (Smil 1999). Dung contributes about 2.5% to the total combustion of bio fuel (wood, charcoal, residues and dung) in the world (Ludwig et al. 2003), which translates to 0.1–0.4% of the world's total energy consumption (Marufu et al. 1997). However, there is a lack of reliable bio fuel consumption data (Kituyi et al. 2001). This holds also for the fraction of N_2O emitted during burning, as it is unstable in smoke and difficult to measure. Most of the N in dung is converted to N_2 and NO_x (= $NO + NO_2$) (e.g., Hegg et al. 1990). It contributes to the formation of smog and to N in rain and dry atmospheric depositions. The IPCC default emission factor for burning dung (7 g per kg N) has been used as the mean in the current calculations.

Emissions from animal wastes from confined animals during storage and handling

Most pigs and poultry, and approximately 40% of the cattle are kept in confinements, where the animal wastes are stored and handled for some time, until treatment and/or application to land. Stored animal wastes are significant sources of NH_3, N_2O, NO_x CH_4, odor and various volatile organic compounds, depending on type of animal waste, management and storage conditions.

Emissions of N_2O from waste storages depend on whether dung and urine are collected unmanaged in corrals and paddocks, or stored anaerobically as slurry in pits and lagoons (with or without anaerobic fermentation for biogas collection), or amended with litter in deep litter stables. Alternatively, dung and urine are separated to yield stacked manure and liquid slurry, with or without subsequent composting of the stacked manure and (anaerobic and/or aerobic) treatment of the liquid slurry. When stored as anaerobic slurry, N_2O emission is low, but NH_3, and CH_4 emissions are high, depending on the cover of the slurry and mixing rate (e.g., Amon et al. 2002). When stored in deep litter stables, emissions of N_2O, NH_3 and CH_4 are relatively high, depending on rate of litter addition and mixing. Emissions from stacked manure depend on the stacking, density, litter addition and temperature of the manure; the higher the density the lower the emission of N_2O and NH_3 but the higher the emissions of CH_4 (Dewes 1996; Amon et al. 2001; Webb et al. 2004). There are no reliable data about emissions of N_2O from unmanaged wastes in corrals and paddocks in region II countries yet.

IPCC emission factors range from 1 g per kg N in anaerobic slurries in lagoons and pits to 20 g per kg N in solid waste in heaps, corrals and paddocks (Table 4). However, there are no accurate inventories of the type of animal waste storages and their managements in practice. We used an overall mean of 10 g per kg N in the animal waste storages, and analysed the effects of variations in emission factor for different regions on the total outcome.

Emissions from animal wastes following application to land

Roughly between 18 and 50 Tg N in animal wastes from (temporarily) confined animals is applied annually to arable land and grassland to fertilize the soil. Available studies suggest that the N_2O emissions from applied animal wastes tend to be higher from pig slurry than from cattle slurry, while anaerobic digestion and increased storage time of the wastes prior to application decrease N_2O emissions after application to land (e.g., Clemens and Huschka 2001; Amon et al. 2002; Velthof et al. 2003). In general, emissions tend to be higher following application of animal wastes to arable land compared to grassland. Further, emissions tend to be higher from wet soils compared to dry soils and from soils poor in organic carbon compared to soils rich in organic carbon

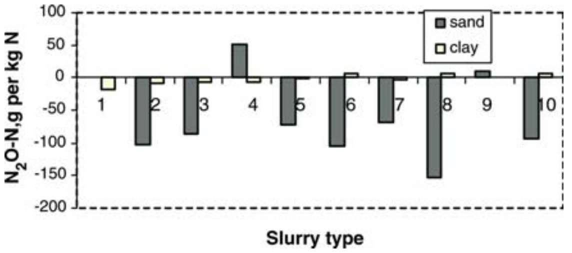

Figure 4. Differences in N_2O emissions between anaerobically digested and undigested pig wastes (N_2O emissions from digested minus N_2O emissions from undigested wastes) following application to a sandy soil and a clayey soil. The 10 wastes were derived from pigs that were fed different rations (see Table 5; after Velthof et al. 2005).

(e.g., Velthof et al. 2003). Also the application method (surface application versus injection) may have an effect. Evidently, the default IPCC emission factor (12.5 g N_2O–N per kg N) does not account for these variations.

Anaerobic digestion of animal wastes is a mean of providing bio fuel to many households in Southeast Asia, and is also becoming popular in some Western Europe countries as a means to mitigate greenhouse gas emissions from animal wastes (Amon et al. 2002). Interestingly, anaerobically digested wastes may emit less N_2O than undigested wastes per unit N applied, because the easily degradable organic carbon in the undigested wastes can fuel the denitrification of NO_3^- present in soil (Clemens and Huschka 2001). This was confirmed by results from an experiment in which 10 different digested and undigested pig wastes were applied to a bare clay soil and a bare sand soil (Figure 4). When applied to the sand soil, undigested and digested wastes emitted on average 110 and 48 g N_2O–N per kg, and when applied to the clay soil 16 and 13 g N_2O–N per kg, respectively. Mean differences between the sand and clay soils were large, and were related to the amount of degradable organic carbon and NO_3^- in the soils (Velthof et al. in preparation).

The composition of the diet influences the composition of the animal wastes and subsequently the emissions of NH_3 and CH_4 during its storage and the emissions of N_2O following its application to soil. Decreasing the protein content decreased the emission of NH_3 from wastes during storage and strongly decreased the emission of N_2O following the application of the wastes to soil (Table 5). Addition of salt ($CaSO_4$) has been introduced as a means to influence the cation to anion ratio in the urine and thereby its pH and potential for NH_3 loss. However, it did not have much effect on NH_3 losses during storage, but surprisingly almost nullified the effect of lowering protein in the animal feed on emissions of N_2O following application of the wastes to soil. Doubling total carbohydrate content slightly increased the emissions of N_2O following application of the wastes to both soils. In contrast, increasing the content of fermentable carbohydrates in the feed increased the emissions of N_2O from the sand soil but not from the clay soil. These results indicate that there are complex interactions between soil type and the composition of animal wastes, which are reflected in large variations of N_2O emissions from some soils upon modest variations in diets. However, these interactions are only partly understood.

So far, the number of studies is too limited and the results are too variable to be able to derive specific emission factors for animal waste type, soil type and land use that can be used in the estimation of N_2O emissions following animal waste application. FAO and IFA (2001) recently calculated a mean emission factor of 6 g N_2O–N per kg N from animal wastes applied to land (median 3; SD 7), using 45 studies. Evidently, this emission factor is much lower than the current default IPCC emission factor (12.5 g N_2O–N per kg N). Based on these results, we used a default value of 6 g N_2O–N per kg N in the animal waste applied, and analysed the effects of possible variations in emission factor due to differences in soil type (wetness), animal waste and land use (grassland versus arable land) on the global N_2O emissions.

Indirect emissions from animal wastes

Indirect N_2O emissions are derived from N that originated from animal wastes, but escaped from the wastes either via NH_3 and NO_x volatilization or via N leaching and runoff, and is then in another location transformed into N_2O. Using animal numbers of the year 2000 (Table 1) and the N excretion and NH_3 loss fractions from Bouwman et al. (1997), estimated total NH_3 losses from animal wastes were 23 Tg in 2000. The estimated amount of N lost via leaching and run off has been estimated to range between 10 and 30%; the

Table 5. Effects of variations in the composition of diets for fattening pigs on $NH_3$and CH_4 emissions from the wastes during storage, and on N_2O emission from the wastes following application to sand and clay soil.

Diet	Composition of the diets				Emissions during storage and following application of wastes to soil			
	Crude protein (g per kg)	$CaSO_4$ (g per kg)	Non-starch carbohydrates (g per kg)		NH_3 emission during storage, (g N per kg slurry)	CH_4 emission during storage, (g C per kg slurry)	N_2O emission from sand soil, (g N per kg N applied)	N_2O emission from clay soil, (g N per kg N applied)
			Total	Fermentable				
A	142	0	189	83	1.1	4.8	10	11
B	180	0	189	83	2.4	6.1	179	7
C	142	17	189	83	1.1	5.0	73	26
D	180	17	189	83	2.2	5.5	93	8
E	161	8.5	129	62	1.3	4.4	52	17
F	161	8.5	245	62	1.4	5.8	95	28
G	161	8.5	129	104	2.0	1.8	166	11
H	161	8.5	245	104	1.3	5.0	110	19
$I_{ref.}$	180	0	129	83	2.1	3.3	185	9
J	161	8.5	189	83	1.5	5.4	148	22

Diet I is the reference diet (after Velthof et al. 2005).

higher estimate is probably realistic for grazing animals in region I countries and the lower estimate for grazing animals in region II countries and for animal waste storages. This yields a total leaching loss of about 11 Tg for 2000.

The current IPCC default emission factors are 10 for N from NH_3 and NO_x volatilized from animal wastes, and 25 g N_2O–N per kg N from animal wastes following leaching and run off. The emission factor for N from leaching and runoff seems relatively high; we used a mean emission factor of 10 g per kg N for indirect emissions (Table 4).

Global N_2O emission from animal wastes

Total estimated N_2O emissions from animal wastes were 1.5 Tg N_2O–N in 2000 (Table 6). This estimate is lower than the mean estimate of Mosier et al. (1998), but it is within their uncertainty range. Wastes from grazing animals were the biggest source (41%), followed by indirect sources (27%), animal wastes in stables and storages (19%), animal wastes applied to land (10%) and burning dung (3%). About 60% of the emissions occur in developing countries (region II countries) and 40% in region I countries. Non-dairy cattle is the largest source (44%), followed by dairy cattle (16%), sheep (12%), pigs (9%), and poultry (6%).

Estimated total emissions appear to be not sensitive (changes <10%) to a three-fold change in the fraction of N lost via leaching and run off, in the fraction of dung used for burning, and in the emission factor for burning of dung. Total emissions are medium sensitive (changes 10–50%) to changes by a factor of 3 in the emission factor for animal wastes applied to land and in the emission factor for animal wastes in stables and storages. Total emissions are sensitive (changes >50%) to changes by a factor of 3 in the emission factor for grazing animals and in the emission factor for indirect sources. Estimated total emissions are also sensitive to changes by a factor 2 in N excretion by cattle, but medium sensitive to changes by a factor 2 in N excretion by sheep and not sensitive to changes by a factor 2 in N excretion by the other animals. Changes in the ratio of N deposited in confinement (stables, paddocks) and in pasture, and changes in the leaching fraction (in the range of 10–30%) contribute to relatively minor changes (< 10%) in total emissions, depending on the emission factors chosen. An increase in animal numbers by 44% in the year 2030 leads to a less than proportional increase in N_2O emissions, when the increase in animal number occurs predominantly in developing countries, because of the lower N excretion and drier conditions (suggested to cause less N_2O production per unit N).

Discussion

How to reverse the trend of increasing N_2O emissions from animal production systems?

The projected increase in animal number and the likely increase in N excretion per animal head for

Table 6. Calculated global N_2O emissions from animal systems, differentiated per animal species and N_2O source, in Gg N_2O–N per year.

Animal species	Sources of N_2O (Gg per year)					
	Burning dung	Grazing animals	Stables & storages	Applied wastes	Indirect emissions	Total emissions
Dairy cattle	4	73	66	36	66	245
Non-dairy cattle	38	321	82	44	194	679
Buffalo	6	27	15	8	25	81
Camels	1	4	2	1	4	14
Horses	2	16	7	4	11	40
Sheep	0	148	9	5	30	192
Goats	0	45	4	2	10	62
Pigs	0	0	63	34	42	139
Poultry	0	0	39	21	30	90
Total	51	635	288	156	412	1543

Animal numbers were taken from 2000 (Table 1) and N excretion per animal species according to Table 3.

the year 2030 will increase the N_2O emissions from animal production systems by more than 40% relative to current estimates. This trend is opposite to the objectives of the Kyoto Protocol, which require an average decrease in greenhouse gas emissions of 50–60% by 2030 relative to 1990. Therefore, how to reverse the trend of increasing emissions from animal production systems is a relevant question. The key answer will probably be found in the management of the animal waste, as other factors are difficult to control. Changes in number of animal species are driven by the increasing quest for food by the increasing human population. In theory, there is scope for lowering per capita animal protein consumption and for replacing animal protein by plant protein, but this seems not easy to realize in practice (e.g., Smil 2002). There is also scope for decreasing protein level in intensively managed grass-based cattle systems in affluent countries (e.g., Figure 3; Van Bruchem et al. 1999), but animal productivity in many developing countries is limited by poor feed quality and low protein content, suggesting that on a global scale the scope for lowering mean N excretion per animal head while maintaining productivity is small. Hence, the potential effect of lowering protein content in the animal rations on global N_2O emissions is estimated to be small (<10%).

A first line of thought to drastically lower emission is via large-scale introduction of anaerobic digesters. Emissions of N_2O will be low when animal wastes are collected and stored anaerobically. Anaerobic digestion of animal waste during storage has the additional advantage of producing CH_4 to be used as bio fuel. It encompasses the perspectives of minimizing emissions of odours, NH_3, N_2O and CH_4 during storage (Amon et al. 2002), and minimizing emissions of N_2O following application to land (Clemens and Huschka 2001; Velthof et al. 2003). During anaerobic digestion a significant fraction of the organically bound N is mineralized to ammonia and as a consequence, the effectiveness of the animal waste as N fertilizer is increased following application of the digested wastes to land, which is another beneficial side effect. However, the digested animal wastes has to be injected in the soil or applied under irrigation, to minimize NH_3 losses following application, and hence to minimize indirect N_2O emissions (e.g., Jarvis and Pain 1997). Our preliminary estimates (not shown) suggest that anaerobic digestion of *all* animal wastes with collection and use of the CH_4 generated, in combination with low NH_3 emission application techniques, could half the total N_2O emissions from global animal production. Anaerobic digestion of animal wastes has the additional benefits of minimizing emissions of CH_4 and of replacing fossil energy (and associated CO_2 emissions). However, it requires that animals are kept in confinements and that the dung (and urine) is collected and stored anaerobically. It also requires that all animal feed has to be harvested and transported to the confined animals. For proper emissions accounting and to circumvent emission swapping, the energy costs and CO_2 emissions associated with harvest and transport have to be accounted for. Furthermore, animal welfare and animal health issues have to be considered too, as well as the issue of proper nutrient management (Sims et al. 2004). There are also other side effects like landscape maintenance, biodiversity and social-cultural issues, when grazing ruminants should be housed. Evidently, anaerobic digestion of the animal waste during storage only seems an option for small-scale digesters as practices in some developing countries and for intensively managed animal production systems. We estimate that anaerobic digestion of the animal waste can be an option for not more than one-quarter of the global amount of animal wastes produced (from housed cattle, pigs and poultry). Implementation of anaerobic digestion in practice at this scale could decrease the global N_2O emissions from animal production systems by 10–20%.

A second line of thought to lower N_2O emission is by decreasing N losses and improving N use efficiency. Currently, only a fraction of the animal wastes is used effectively for crop growth. Improving the efficiency of utilization of N from animal wastes will decrease indirect N_2O emissions from animal production systems and has the potential benefit of replacing fertilizer N and thereby decreasing N_2O emissions associated with N fertilizer production and use. However, cashing the benefits of improving N use efficiency can only be done by integrating the crop production subsystem, that provides the animal feed, and the animal production subsystem that provides the animal waste to the crop production system. Exploring the benefits and constraints of such systems requires integrated studies that follow a chain approach and that consider all social, economic and ecological impacts and trade-offs. Results of our simple calculations suggest that improving animal waste management combined with implementation of techniques for low-emission stables, animal storage systems and application of animal manure could potentially decrease N losses from global animal production systems for housed animals by some 10–20 Tg N, which in theory could replace 10 Tg fertilizer N.

In conclusion, the perspectives for lowering global N_2O emissions from animal production systems by modifying animal waste management systems, while maintaining animal productivity seem to be limited. Large-scale implementation of anaerobic digestion of animal wastes and improvements in N use efficiency could decrease total emissions by 10–20% and 5–15%, respectively. Achieving these percentages requires a huge effort, and is still insufficient to meet the targets of the Kyoto Protocol in the long term. This conclusion illustrates a dilemma of extension and intensification of animal production.

How to cope with uncertainties in emission estimates of animal production systems?

The uncertainty range in the global N_2O emission estimates of animal production systems is larger than the 50–60% mitigation required in 2030, as targeted by the Kyoto Protocol, and assuming a proportional mitigation in all sectors involved. These uncertainties in emission estimates and particularly in emission factors hinder the identification and prioritizing of suitable mitigation policies and strategies at country and global levels, but also at farm level where the actions have to be taken. Mitigation strategies need a sound basis, to be able to convince farmers to take proper actions and to justify investments. Tailor-made strategies have the potential to be most effective, as they take the specific conditions of the farm into account, but they require accurate emission estimates and a thorough understanding of controlling factors of N_2O emissions and their interactions.

When dealing with uncertainties, it is useful to distinguish fundamental from operational uncertainties. Here, fundamental uncertainties arise from the structure (and upscaling) of the inventory procedures, while operational uncertainties arise from uncertainties in the activity data (animal number, $Nex_{(T)}$ and $AWMS_{(T)}$) and emission factors. There are huge spatial and temporal variations, a lack of accurate activity data and a lack of knowledge (true uncertainty) about the controls of underlying processes. Assessing fundamental uncertainties requires independent checks via verification measurements and/or simulation modelling. Assessing operational uncertainties can be done by Monte Carlo simulations (e.g., Van Aardenne 2002). Decreasing uncertainties simply requires more data and better insight and understanding.

Our calculations suggests that the importance of variables contributing to uncertainty in the global emission estimate roughly increase in the order: animal number < N excretion per animal < N excretion per type of $AWMS_{(T)}$ < emission factor per $AWMS_{(T)}$ and for animal waste applied to land. Uncertainties related to $AWMS_{(T)}$ originate from the poor availability of accurate data about $AWMS_{(T)}$, from the lack of information about the actual handling and management of animal waste in the $AWMS_{(T)}$ and about the consequences of this management on N_2O emissions. This suggests that more accurate information about the actual management of animal wastes in practice might be as relevant for accurate emission accounting and identification of mitigation strategies as improving the accuracy of emission factors. The calculations suggest that uncertainties in the emission factors for grazing animals and for indirect emissions have the largest effects on the global N_2O emission estimates. The uncertainties in N excretion of cattle have a large impact, simply because of the large number of cattle and their relatively high N excretion. This simple rating of uncertainties does provide suggestions for setting priorities in research and environmental policy. For developing sound mitigation policies and strategies, uncertainties in inventories have to be decreased, and this is done most economically by focusing on the largest sources of N_2O and the largest sources of uncertainties.

There is still a fair amount of true uncertainty about the N_2O producing processes and controls, and the traditional distinction into N_2O from 'aerobic' nitrification and 'anaerobic' denitrification has been challenged, recently. Firstly, nitrifier denitrification, a pathway of N_2O production by nitrifiers is probably enhanced by low O_2 conditions (Poth and Focht 1985; Webster and Hopkins 1996), and the differences between enzymes in nitrifiers might be larger than so far assumed (Wrage et al. 2004a, b). This may lead to the insight that N_2O production is related to the microbial community and that the reaction to environmental factors may be different (Dundee and Hopkins 2001; Wrage et al. 2004a, b). Secondly, aerobic denitrification might in some organisms be coupled to heterotrophic nitrification (Papen et al. 1989; Robertson and Kuenen 1990)). Thirdly, fungi have recently been found to dominate the N_2O production in grassland in Northern Ireland (Laughlin and Stevens 2002). Fungi often lack N_2O-reductase (Shoun et al. 1992), so that N_2O is the end-product. Fourthly, there is evidence to suggest that abiotic reduction of HNO_2 in acid soils might be a more important source of N_2O than generally assumed (e.g., Venterea and Rolston 2002). Such abiotic formation of N_2O might occur in urine patches following hydrolysis of urea and the subsequent nitrification of NH_4^+. To sum up, the possibilities for N_2O production seem much broader than traditionally assumed. The relevance of these novel findings for emission accounting and mitigation strategies in animal production systems still has to be figured out. Hypotheses and relationships need to be formulated about the controls of the various N_2O sources, and data bases need to be developed to test the hypotheses and relationships under various environmental and management conditions. Evidently, further work is needed to be able to decrease uncertainties in global N_2O emission estimates of animal production systems.

Conclusions and recommendations

Animal production systems are relatively large and complex sources of N_2O. The uncertainties in the emission estimates are large, due to the many complexities involved and the lack of accurate data, especially about N excretion and the management of animal wastes in practice. The expected increases in N_2O emissions following the projected increase in animal number till 2030 seem to be much larger than the potential decreases in N_2O emissions through feasible mitigation measures, suggesting that N_2O emissions from animal production will continue to increase. The best mitigation strategies seem anaerobic digestion of animal waste during storage and improving N use efficiency at the whole system level.

Various actions need to be taken to decrease the uncertainties in global N_2O emission estimates and thereby to allow the development of sound mitigation policies and strategies. We recommend the following actions:

1. Better use of existing data and relationships to improve the accuracy of N excretion estimates per animal species and $AWMS_{(T)}$. A further differentiation and characterization of $AWMS_{(T)}$ could be achieved through new census and inquiry data. A further differentiation of the emission factor for applied animal waste according to soil type (wetness, organic carbon) and manure type may improve the accuracy, and at the same time help to define mitigation strategies.

2. Hypotheses driven research and development of data bases to test the hypotheses about the controls of the various N_2O sources in animal production systems.
3. New census data and measurements are especially needed in regions with large populations of cattle and other animals and as yet little experimental data, such as in Region II countries. This holds especially for the Indian continent, Latin America and Africa.
4. Mechanistic simulation models should be further developed and applied, so as to verify the estimates of current inventory procedures and to explore the effects of new hypotheses and findings.
5. Verification and validation through inverse modelling and direct measurement are needed to assess the fundamental uncertainty in the global emission estimate of animal production systems.

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