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Nitrous Oxide Emissions from Cattle Production Systems and Mitigation Options

By

B. AMON, TH. AMON, CH. ALT, G. MOITZI & J. BOXBERGER[1)]

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Summary

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Agriculture contributes significantly to anthropogenic N_2O emissions. Nitrous oxide is formed by biological nitrification and denitrification. Sources of nitrous oxide are direct emissions from agricultural soils, direct emissions from animal waste management systems and indirect emissions from agricultural N input. The Institute of Agricultural, Environmental and Energy Engineering measured nitrous oxide emissions from straw based cattle production systems. Milking cows housed in a tying stall emitted 220 g N_2O $lu^{-1}yr^{-1}$. Beef cattle in a sloped floor house emitted 101 g N_2O $lu^{-1}yr^{-1}$ (5.0 kg straw $lu^{-1}d^{-1}$), and 194 g N_2O $lu^{-1}yr^{-1}$ (2.5 kg straw $lu^{-1}d^{-1}$), respectively. Stacked farmyard manure emitted 52.1 g N_2O t^{-1} (summer experiment), and 79.4 g N_2O t^{-1} (winter experiment). Aeration of farmyard manure by composting reduced nitrous oxide emissions to 34.1 g N_2O t^{-1} (summer experiment), and 47.2 g N_2O t^{-1} (winter experiment). Improvement of overall N efficiency is the most effective way to reduce both direct and indirect nitrous oxide emissions.

Introduction

Nitrous oxide contributes to greenhouse warming of the atmosphere because it traps part of the thermal radiation from the earth´s surface. On a per molecule basis, N_2O is 310 times more potent than carbon dioxide. It is also involved in the depletion of the ozone layer in the stratosphere. In the past 20 years, atmospheric N_2O concentration rose by 0.8 ppb or 0.25 % per year (EK 1994, BEESE 1994).

[1)] Institute of Agricultural, Environmental and Energy Engineering, University of Agricultural Sciences, Nussdorfer Laende 29 – 31, A-1190 Vienna, Austria.

Agriculture contributes significantly to anthropogenic N_2O emissions. Anthropogenic sources emit 5.7 Tg N_2O-N per year, 3.5 Tg of which result from agricultural soils (IPCC 1995). However, those estimates include a high range of uncertainty of ± 50–60 %. This is due to the complex interactions between physical, chemical and biological variables that lead to highly variable N_2O emissions both in time and space.

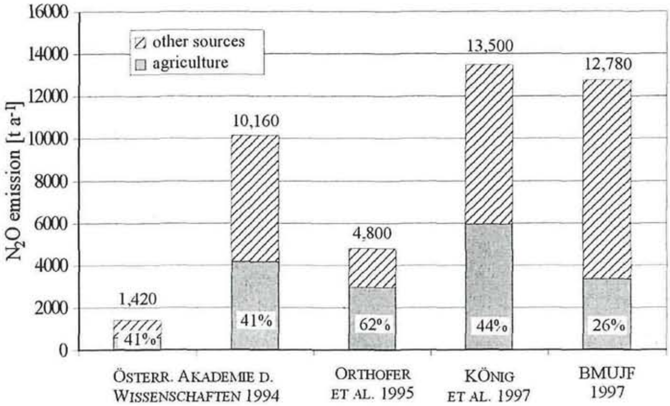

Fig. 1. Estimates of Austrian N_2O emissions.

Fig. 1 gives different estimates of Austrian N_2O emissions. Net emissions as well as agriculture´s share show considerable variation. This is due to the high uncertainties connected with N_2O emissions. There is a need for more research to fill existing gaps of knowledge. Country specific emission factors are needed in order to estimate N_2O emissions more accurately.

However, it is well agreed that agriculture is one of the major contributors to anthropogenic N_2O emissions and that there is a need to reduce agricultural N_2O emissions (e.g. MOSIER & al. 1998a, COLE & al. 1997).

IPCC 1995 guidelines for national greenhouse gas inventories only included direct field emissions from soils fertilised with mineral N (IPCC 1995). Thus, agricultural N_2O emissions were underestimated. In the "1996 revised guidelines for national greenhouse gas inventories" two more agricultural N_2O emission sources were identified and included in the inventory: emissions from animal production, and N_2O emissions indirectly induced by agricultural activities (IPCC 1997). By including those additional sources in the inventory, global N_2O emissions from agriculture rose from 3.5 Tg N_2O-N yr^{-1} to 6.3 Tg N_2O-N yr^{-1} (Table 1). However, understanding of N_2O emissions from animal waste management systems and from indirect N_2O emissions is still very poor and the estimates have to be recalculated as new data become available (MOSIER & al. 1998a).

Table 1. Agricultural N_2O emissions calculated after IPCC 1995 and IPCC 1997.

Source	IPCC 1995 [Tg N_2O-N yr^{-1}]	IPCC 1997 [Tg N_2O-N yr^{-1}]
1 direct emissions from agricultural soils	3.5	2.1
2 direct emissions from animal production	---	2.1
3 indirect emissions induced by agricultural activities	---	2.1
Sum	3.5	6.3

Nitrous oxide is formed during biological nitrification and denitrification (FIRESTONE & DAVIDSON 1989). Nitrification is an aerobic process where ammonium is oxidised to nitrate via nitrite. Ammonium availability strongly influences the nitrification rate. Optimal temperature ranges from 30 to 35 °C, below 5 °C no nitrification can be observed. A soil volumetric water content of 60 % is optimal for nitrification. A higher soil water content hinders oxygen supply, a lower soil water content limits microbial activity and transportation of gases and nutrients.

Denitrification is an anaerobic process where nitrate is reduced to N_2 via NO and N_2O. NO and N_2O are emitted if denitrification is incomplete. NO_3^-, NO and N_2O act as electron acceptors when oxygen is lacking. Denitrification is a function of oxygen supply, carbon availability, temperature, pH, water content and concentration of NO_3^-, NO and N_2O.

Denitrification needs an oxygen concentration below 5 vol. %. High concentration of available organic carbon, pH between 6 and 8, temperature above 10 °C and volumetric water content of more than 80 % support denitrification.

N_2O will be released at any stage of the livestock production system where conditions are favourable for nitrification or denitrification (CHADWICK & al. 1999). This requires a whole system approach when carrying out emission measurements.

This paper presents new findings of N_2O emissions from cattle production systems and lists possible options to reduce N_2O emissions.

Materials and Methods

N_2O emissions were measured from a dairy cattle house, a beef cattle house, and during farmyard manure storage. Concentrations of N_2O were continuously analysed by high resolution FTIR (Fourier transform infrared) spectroscopy. FTIR spectroscopy is based on the principle that individual gases have distinct infrared absorption features. Every IR spectrum contains the information of all IR radiation absorbing gases between a radiation source and a detector (GÜNZLER & BÖCK 1983, STAAB 1991). Exhaust air from animal houses or manure stores is a mixture of up to 200 different gaseous components. In order to avoid cross-sensitivities that would result in wrong concentration readings, the spectral resolution of the FTIR spectrometer has to be high. The applied FTIR spectrometer has a spectral resolution of 0.25 cm^{-1}. It operates using a white cell with 8 m light path. For nitrous oxide ambient air level marks the detection limit.

The dairy cattle and beef cattle house were force-ventilated. Ventilation rate and gas concentration were analysed in the forced ventilation ducting. Ventilation rate varied between 150

m^3 h^{-1} lu^{-1} in winter[2] and 400 m^3 h^{-1} lu^{-1} in summer. Gas concentrations were alternately measured in the incoming air and in the exhaust air. Measurements were continuously carried out for 24 hours a day during each experiment.

The tying stall housed 12 dairy cows. It was alternately operated as a slurry based and as a straw based system to enable a comparison between both systems. For the straw based system wooden boards were laid on the dung grids behind the cows and 2 kg of straw per cow and day were littered down. The farmyard manure was mugged out twice a day.

Table 2 shows date of trial, climatic conditions inside and outside the housing, and milk yield per cow.

20 beef cattle were housed in a sloped floor housing system. Here we investigated the influence of amount of straw littered down on nitrous oxide emissions. Two trials with 5.0 kg straw $lu^{-1}d^{-1}$, and 2.5 kg straw $lu^{-1}d^{-1}$, respectively, were carried out, and emissions were measured several times in course of the year. Table 3 gives date of trial, climatic conditions inside and outside the housing, and live weight per beef cattle.

Table 2. Overview of the conditions during emission measurements from a tying stall for dairy cows.

experiment	**date**	**climatic conditions**				**milk yield**
		$temp_{out}$[a] [°C]	$temp_{in}$[b] [°C]	rh_{out}[c] [%]	rh_{in}[d] [%]	[kg cow^{-1}]
Slurry I	10-16 to 10-23	8.1	12.6	87.2	58.7	22.4
Straw I	11-01 to 11-08	5.5	14.6	89.0	61.8	23.0
Straw II	11-27 to 12-06	-3.0	8.1	90.8		
Slurry II	12-11 to 12-20	-3.1	14.5	97.7		18.5
Slurry III	01-30 to 02-06	-3.4	9.4	81.4	57.7	16.1
Straw III	06-16 to 06-26	14.3	19.4	70.1	73.7	16.7
Slurry IV	06-26 to 07-08	17.5	20.2	61.6	63.5	16.7
Straw IV	07-24 to 08-01	17.9	20.9	65.8	65.0	16.6
Slurry V	08-04 to 08-11	19.9	22.1	62.9	66.7	16.8
Slurry VI	10-17 to 10-31	3.6	13.1	70.9	58.6	20.0

[a]temperature outside [b]temperature inside [c]relative humidity outside [d]relative humidity inside

Table 3. Overview of the conditions during emission measurements from a sloped floor beef cattle house.

experiment	date	climatic conditions				live weight
		$temp_{out}$[a] [°C]	$temp_{in}$[b] [°C]	rh_{out}[c] [%]	rh_{in}[d] [%]	[kg $bull^{-1}$]
much straw I	10-03 to 10-15	8.3	n.m.[e]	89.5	n.m.[e]	485
little straw I	11-18 to 11-27	1.5	n.m.[e]	90.9	n.m.[e]	532
much straw II	01-10 to 01-30	-0.5	10.3	74.7	70.9	638
much straw III	07-08 to 07-22	16.4	18.2	75.1	69.8	197
little straw II	08-14 to 08-28	20.0	21.0	73.3	66.5	251
much straw IV	09-16 to 09-30	12.9	17.2	73.6	60.7	298

[a]temperature outside [b]temperature inside [c]relative humidity outside [d]relative humidity inside [e]not measured

[2] lu = livestock unit = 500 kg live weight

In a sloped floor housing the animals lie on a mattress of straw and manure, that has a slope towards the feeding area. The animals continuously tread part of the mattress towards the dung alley. The dung alley was mugged out every day.

For the determination of the air flow over stored manure and during and after manure spreading ILUET[3] has developed a large open-dynamic-chamber (Fig. 3, AMON & al. 1996). The mobile chamber covers an area of 27 m^2 and can be built over emitting surfaces in the animal housing, on manure stores and over spread manure. Fresh air enters the chamber at the front. In the chamber the fresh air accumulates the emissions and leaves the chamber on the far side. Gas concentrations are measured alternately in the incoming and in the outgoing air. The differences in concentration of specific gases between the incoming and the outgoing air represent the emissions from the substrate inside the chamber. Measurements are performed continuously and on-line by high resolution FTIR spectroscopy. The air flow through the chamber is recorded continuously by a fan-based flow meter. During farmyard manure storage the air flow rate was at about 2,000 $m^3 h^{-1}$.

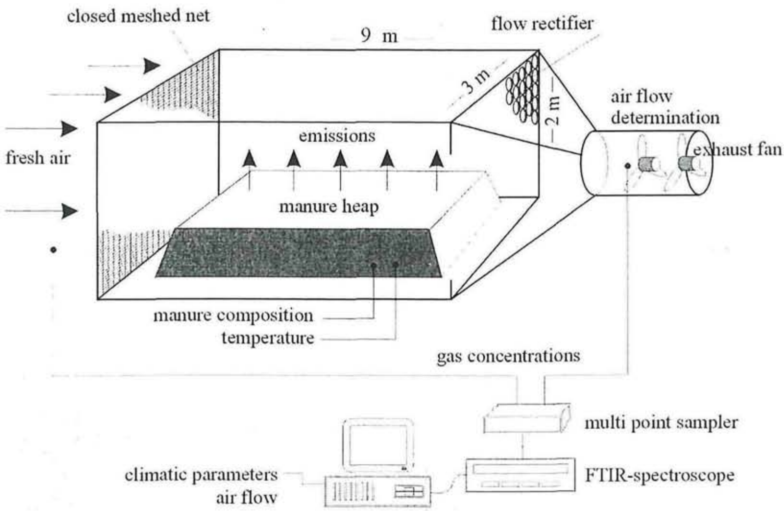

Fig. 3. Large open-dynamic chamber developed by ILUET (AMON & al. 1996).

ILUET's emission measurements follow a whole systems approach in order to assess environmental impacts of manure management systems. In the sloped floor housing, farmyard manure was mugged out on a daily basis. It is common practice to store fresh farmyard manure near the housing for some days prior to any treatment that might be applied during storage. ILUET's measurements included emissions from the housing and during farmyard manure storage (as shown below). In addition, emission measurements during a 10-day storage of freshly mugged out farmyard manure without any treatment were carried out in order to assess emissions from the complete manure chain. The fresh farmyard manure from the beef cattle house was brought into ILUET's large open-dynamic-chamber to assess emissions from stored farmyard manure as soon as it had left the housing. Emission measurements from about 4 t of fresh manure lasted for 10 days. Methodology for emission measurements was the same as during the farmyard manure storage experiments that are described below. Measurements were carried out parallel to the trials "much straw II" and "little straw I" (see Table 3).

[3] ILUET = Institute of Agricultural, Environmental and Energy Engineering

Farmyard manure can either be anaerobically stacked or aerobically composted. To assess nitrous oxide emission of both ways of farmyard manure treatment, two heaps of farmyard manure (each about 7 t) were stored on concrete slabs. Seepage water emissions were collected and analysed for their N content. One heap was composted aerobically, which means it was turned seven times during the storage period. The other heap was stacked anaerobically, with no manipulations performed during the storage period. The large open-dynamic-chamber was build up over the manure heaps to collect the emissions. Each heap was measured continuously for two days, after which the large open-dynamic chamber was moved to the other heap. The storage period lasted for 80 days. The experiment was carried out twice: once under summer conditions and once under winter conditions. Table 4 gives the farmyard manure composition at the beginning of the experiments and the mean temperature inside the manure heap during the storage period.

Table 4. Farmyard manure composition and mean temperature inside the manure heaps.

experiment	**DM[a] [%]**	**N_t[b] [kg t^{-1}]**	**NH_4-N [kg t^{-1}]**	**C/N**	**pH**	**Temp. [°C]**
summer						
composted FYM[c]	28.3	6.60	1.10	14	7.55	45.0
stacked FYM	20.4	6.39	1.17	14	7.43	35.3
winter						
composted FYM	22.1	6.69	0.63	16	8.7	34.3
stacked FYM	21.2	6.31	0.43	15	8.2	22.4

[a]dry matter [b]total nitrogen [c]farmyard manure

The effects of treatments were tested in an analysis of variance using the general linear models procedure. Mean rates of N_2O emission were compared by one-way ANOVA followed by t-test or Bonferroni multiple comparisons test where appropriate (SACHS 1992).

Results and Discussion

Nitrous oxide emissions from the dairy cow house averaged 0.61 g N_2O $lu^{-1}d^{-1}$ in the slurry based system and 0.62 g N_2O $lu^{-1}d^{-1}$ in the straw based system. The difference is not significant. Nitrous oxide emissions showed considerable variation in course of the year with higher emissions during summer time (Table 5). More details on emission rates measured from the dairy cow house can be found in AMON 1998. CHADWICK & al. 1999 give an emission factor of 0.80 g N_2O $lu^{-1}d^{-1}$ for milking cows in the UK.

Table 5. Daily nitrous oxide emissions from a tying stall for dairy cows.

	N_2O [mg $lu^{-1}d^{-1}$]	
experiment	mean	standard error
slurry I	153.56	30.36
slurry III	316.64	65.75
slurry IV	728.25	128.61
slurry V	1166.73	116.16
straw I	308.34	80.20
straw II	279.80	42.37
straw III	625.50	118.60
straw IV	1101.06	265.29

Table 6. Nitrous oxide emissions from beef cattle housed in a sloped floor housing (experiments "much straw II" and "little straw I").

N_2O emission	experiment	
[g (t FYM)$^{-1}$yr^{-1}][a]	much litter (5.0 kg straw lu^{-1} d^{-1})	little litter (2.5 kg straw lu^{-1} d^{-1})
N_2O from beef cattle house	5.26	3.25
N_2O from storage of fresh manure	4.81	16.71
SUM	10.07	19.42

[a] FYM = farmyard manure

The amount of straw strongly influences nitrous oxide emissions from the sloped floor beef cattle house (Table 6). Values in Table 6 are expressed as g N_2O per t farmyard manure produced in the beef cattle house. Data were gathered in the experiments "much straw II" and "little straw I" (see Table 3). The time frame includes the house and the 10-day storage of fresh manure.

With 5.0 kg straw $lu^{-1}d^{-1}$ emissions from the beef cattle house and during storage of fresh manure totalled to 10.07 g N_2O (t FYM)$^{-1}$. 2.5 kg straw $lu^{-1}d^{-1}$ resulted in an emission of 19.42 g N_2O (t FYM)$^{-1}$. When much straw was littered down, about 52 % of net total emissions came from the beef cattle house. The high straw rate gave higher N_2O emissions from the beef cattle house than the low straw rate. When a small amount of straw was used, about 86 % of net total emissions were emitted during storage of fresh manure. N_2O emissions during storage of fresh manure were considerably higher in the low straw system. It is important to include all stages of livestock production in the measurements in order to deduce effective mitigation measures.

Nitrous oxide emissions from the beef cattle house were measured several times in course of the year (see Table 3). Emissions from the beef cattle house were 52.56 g N_2O $lu^{-1}yr^{-1}$ with much straw and 32.49 g N_2O $lu^{-1}yr^{-1}$ with little straw. The difference is statistically significant at $p < 0.05$.

Emissions during 10-day storage of fresh farmyard manure were measured during experiments "much straw II" and "little straw I". Temperature inside the manure heaps increased rapidly at the beginning of the storage due to intensive microbial activity. Outside temperature and season have little influence on emissions during storage of fresh manure. Assuming an annual production of 10 t of farmyard manure per livestock unit (HYDRO AGRI DÜLMEN GMBH 1993), emissions from storage of fresh manure were 48.10 g N_2O $lu^{-1}yr^{-1}$ with much straw and 161.7 g N_2O $lu^{-1}yr^{-1}$ with little straw.

Emissions from the beef cattle house and from storage of fresh manure add up to 101 g N_2O $lu^{-1}yr^{-1}$ in the high straw system and 194 g N_2O $lu^{-1}yr^{-1}$ in the low straw system.

Nitrous oxide emissions during farmyard manure storage were 34.1 g N_2O t^{-1} (compost, summer), 47.2 g N_2O t^{-1} (compost, winter), 52.1 g N_2O t^{-1} (stacked FYM, summer), and 79.4 g N_2O t^{-1} (stacked FYM, winter). Stacked farmyard manure contains both aerobic and anaerobic zones. Organic carbon is available as well. This favours nitrous oxide production from nitrification and denitrification. Composting can significantly reduce nitrous oxide emissions during farmyard manure storage, as oxygen supply prevents denitrification. During the summer experiment, aeration in the compost heap was good. In winter, heavy snowfall wetted the compost and prevented sufficient aeration. This resulted in higher N_2O emissions.

CHADWICK & al. 1999 found nitrous oxide emissions of 1.1 g N_2O $m^{-3}d^{-1}$ for anaerobically stacked farmyard manure which matches well the values found in our experiments. HÜTHER 1999 also found higher N_2O emissions from cattle manure with lower oxygen supply. Her experiments gave N_2O emissions between 0.3 % and 1.5 % of total nitrogen content. Nitrogen losses found in our experiments varied between 0.3 and 0.8 %. The "1996 revised IPCC guidelines" (IPCC 1997) suggest an emission factor for solid storage of 20 g N_2O-N per kg N excreted with a range between 5 and 30 g N_2O-N per kg N excreted. N_2O emissions found in our experiments correspond to a range between 2.7 and 10.2 g N_2O-N per kg N excreted.

Mitigation options for nitrous oxide emissions from agriculture

There are various possibilities to reduce nitrous oxide emissions from agriculture. The key option is to improve N efficiency. N flow cycles must be tightened. If N efficiency is only improved in one stage of the livestock production cycle, N will leak at an other stage and overall nitrous oxide emissions will not decrease. Management options which decrease the amount of external N needed to produce a crop or animal product will decrease both direct and indirect N_2O emissions. The amount of N applied to arable land often greatly exceeds the amount of N necessary for crop and grass to grow. A large part of N input is not recovered in agricultural products, but lost to the environment. Excess N leaks as ammonia, nitrate, nitrous oxide or N_2. N from animal manures must be better recycled in order to replace industrial N fertilisers. Less industrial N fertiliser not only means less nitrous oxide emissions, but also less CO_2 emissions from the fertiliser production process. Animal and crop production systems must be integrated in terms of manure reuse. An integrated way of farming should be given priority to specialised farming (MOSIER & al. 1998b, COLE & al. 1997, MINAMI 1997, VELTHOF & OENEMA 1997, ERISMAN & al. 1998).

N efficiency in crop production is better than in animal production. According to the environmental sustainability and food chain ranking described by GOODLAND 1999 autotrophs such as e.g. legumes, grains and vegetables have the least impact on the environment and are most efficient. Animals such as e.g. swine or cattle are on the other end of the ranking. They have the most impact and are least efficient.

Consumers´ attitude towards less meat consumption improves overall N efficiency (ERISMAN & al. 1998). Less meat consumption is a prerequisite for mitigation of N emissions. Animal production is an essential part of sustainable agriculture. However, the present level of meat consumption is neither sustainable nor healthy. ISERMANN & ISERMANN 2000 state that animal production and animal consumption in the EU greatly exceed the protein requirement of EU population.

ILUET´s measurements gave nitrous oxide emissions from milking cows of 220 g N_2O $lu^{-1}yr^{-1}$. Beef cattle in a sloped floor house emitted 101 g N_2O $lu^{-1}yr^{-1}$ (5.0 kg straw $lu^{-1}d^{-1}$), and 194 g N_2O $lu^{-1}yr^{-1}$ (2.5 kg straw $lu^{-1}d^{-1}$), respectively. Nitrous oxide emissions in both houses were low. Feeding animals diets more closely related to their nutritional requirements and reduction of N in the urine can further reduce nitrous oxide emissions from cattle houses. In straw based systems the amount of straw significantly influences nitrous oxide emissions. More straw results in lower N_2O emissions. Additional measurements are needed to assign emission factors for other cattle house designs such as e.g. sloped floor house for milking cows or deep litter system for beef cattle and suckling cows.

Nitrous oxide emissions during slurry storage are supposed to be low. Slurry stores are anaerobic systems. Thus, N_2O could only be formed by denitrification. Oxidised N is necessary for denitrification. Slurry contains mostly reduced N. The "1996 revised IPCC guidelines" assign an emission factor of 1 g N_2O-N (kg N excreted)$^{-1}$ to slurry stores (IPCC 1997). VELTHOF & OENEMA 1997 suggest an emission factor of 0.05 ± 0.05g N_2O-N (kg slurry N)$^{-1}$. CHADWICK & al. 1999 constructed a nitrous oxide emission inventory for the UK assuming no nitrous oxide emissions from slurry stores. Slurry should not be aerated, to prevent formation of oxidised N and thus creating the prerequisite for denitrification. Slurries with reduced carbon and dry matter content have the potential of further reducing nitrous oxide emissions during slurry storage and after spreading.

Anaerobic stacking of farmyard manure gives rise to nitrous oxide emissions. Farmyard manure is rich in nitrogen and mineralizable organic carbon. Both aerobic and anaerobic zones exist in stacked farmyard manure. Sufficient aeration is essential for a good composting process. Insufficient oxygen supply leads to formation of greenhouse gases. If a good composting process is guaranteed, nitrous oxide emissions are low.

Nitrous oxide emissions from soils after fertiliser application have often been subject to investigations. MOSIER 1994 and BOUWMAN 1996 summarise results of research projects. The amount of N applied to arable land is the main influencing factor on nitrous oxide emissions. N_2O-N emissions can be calculated as 1.25 ± 1.0 % of fertiliser N applied.

Improvement of N fertiliser management can reduce N_2O emissions. This applies to mineral N-fertilisers and manure N, as well. Timing and restriction of rate of application offers potential for reducing N_2O emissions following fertiliser-N applications. Rate and timing of fertiliser application must meet crop demand.

When animal manures are applied to arable land, nitrous oxide emissions are likely to increase as they contain mineralizable N and organic carbon. Manure composition and application technique influence N_2O emissions. Application of manures with reduced mineralizable organic carbon reduces N_2O emissions (DOSCH 1996). Denitrification rate increases with the amount of organic carbon, because denitrifying bacteria need organic carbon to grow (BEAUCHAMP & al. 1989). Slurry treatment, such as e.g. slurry separation or biogas production, that reduces slurry carbon and dry matter content reduces N_2O emissions after manure application.

Slurry injection is likely to result in higher N_2O emissions than surface application. THOMPSON & al. 1987 found an increase in N_2O emissions from 33.6 kg N ha^{-1} (winter broadcast) to 57.9 kg N ha^{-1} (winter injection) and from 4.5 kg N ha^{-1} (spring broadcast) to 18.4 kg N ha^{-1} (spring injection). VELTHOF & OENEMA 1997 give an emission factor of 3 ± 3 kg N_2O-N (kg slurry $N)^{-1}$ for surface application of cattle slurry and an emission factor of 5 ± 5 kg N_2O-N (kg slurry $N)^{-1}$ for injection of cattle slurry.

Various management practices and mitigation techniques offer the possibility to reduce agricultural nitrous oxide emissions. VELTHOF & al. 1998 calculated that a package of measures could reduce agricultural nitrous oxide emissions in the Netherlands by up to 70 %. The most promising option is an improvement of overall N efficiency. This includes a reduction in meat consumption, less industrial fertiliser N input, better reuse of manure N and integrated farming in stead of specialised farming.

Acknowledgements

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