

# Greenhouse gas abatement strategies for animal husbandry

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## Abstract

Agriculture contributes significantly to the anthropogenic emissions of non-CO<sub>2</sub> greenhouse gases methane and nitrous oxide. In this paper, a review is presented of the agriculture related sources of methane and nitrous oxide, and of the main strategies for mitigation. The rumen is the most important source of methane production, especially in cattle husbandry. Less, but still substantial, amounts of methane are produced from cattle manures. In pig and poultry husbandry, most methane originates from manures. The main sources of nitrous oxide are: nitrogen fertilisers, land applied animal manure, and urine deposited by grazing animals. Most effective mitigation strategies for methane comprise a source approach, i.e. changing animals' diets towards greater efficiencies. Methane emissions, however, can also be effectively reduced by optimal use of the gas produced from manures, e.g. for energy production. Frequent and complete manure removal from animal housing, combined with on-farm biogas production is an example of an integrated on-farm solution. Reduced fertiliser nitrogen input, optimal fertiliser form, adding nitrification inhibitors, land drainage management, and reduced land compaction by restricted grazing are the best ways to mitigate nitrous oxide emissions from farm land, whereas, management of bedding material and solid manure reduce nitrous oxide emissions from housing and storage. Other than for methane, mitigation measures for nitrous oxide interact with other important environmental issues, like reduction of nitrate leaching and ammonia emission. Mitigation strategies for reduction of the greenhouse gases should also minimize pollution swapping.

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## 1. Introduction

Global atmospheric concentrations of the most important greenhouse gases carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) have increased significantly within the last 150 years. Stabilisation at today's levels and even reduced concentrations, necessary to reduce climate change and corresponding effects, would require significant reductions in emissions of those gases (IPCC, 2001). These reductions are to be brought about through adoption of mitigation measures from all sectors, e.g. industry, agriculture, energy and households. Agriculture contributes

significantly to total greenhouse gas (GHG) emissions. Approximately 20 and 35% of the global GHG emissions originate from agriculture. These figures are 40 and >50% of the anthropogenic emissions of CH<sub>4</sub> and N<sub>2</sub>O, respectively (IPCC, 2001). Most important agriculture related CH<sub>4</sub> sources are animals and their excreta (manure), whereas, most of the N<sub>2</sub>O is produced in the field (manure excreted during grazing, chemical fertilisers), and from animal houses where straw or litter is used (Freibauer and Kaltschmitt, 2001). The Kyoto protocol specifies that each complying country should provide adequate methods and instruments to quantify, monitor and verify GHG emissions and their reductions. In this paper, we present a summarised overview of the range of approaches for reducing emissions of CH<sub>4</sub> and N<sub>2</sub>O from the various sources in the agricultural

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sector, particularly from livestock systems, with a focus on European farming practices.

## 2. Sources and processes

Methane and N<sub>2</sub>O originate from different cycles. Methane is usually produced following the degradation of carbon (C) components during digestion of feed and manure, whereas, N<sub>2</sub>O is related to the nitrogen (N) cycle with chemical fertilisers and manures as the most important sources.

### 2.1. Methane

The rumen is the most important site of CH<sub>4</sub> production in ruminants (breath), whereas, in monogastric animals, like pigs, CH<sub>4</sub> is mainly produced in the large intestine (flatus). Animal manures, stored indoors in sub-floor pits or outdoors, are also relevant CH<sub>4</sub> sources, since conditions usually favor methanogenesis in both slurry and solid manure heaps (Husted, 1994). Monteny et al. (2001) found the following data for CH<sub>4</sub> produced from enteric fermentation and from manure, respectively, for various animal species (Table 1).

Enteric fermentation is the most important source (approximately 80%) of CH<sub>4</sub> in dairy husbandry, whereas, most (70%) of the CH<sub>4</sub> on pig and poultry farms originates from manures. The wide range in the total CH<sub>4</sub> emission from dairy cows is caused by differences in diets and housing systems (lower values for tying stalls; greater emissions from cubicle houses; Groot Koerkamp and Uenk, 1997).

#### 2.1.1. Enteric fermentation

The rate of CH<sub>4</sub> produced from enteric fermentation in dairy cows depends greatly on the level of feed intake, the quantity of energy consumed (see IPCC, 1997), and feed composition. The three most important factors are: (1) rate of organic matter (OM) fermentation; (2) type of volatile fatty acids (VFA) produced, which strongly determines the excess of hydrogen [H] produced in the gastrointestinal tract and the need for CH<sub>4</sub> production as a sink of excess hydrogen, and (3) efficiency of microbial biosynthesis.

**2.1.1.1. Factor 1.** The rate of OM fermentation is strongly influenced by level of feed intake and the degradation

characteristics of the carbohydrate fraction. For example, Mills et al. (2001) demonstrated, in a theoretical study, that CH<sub>4</sub> production was reduced from 6.6 to 6.0% of the gross energy (GE) consumption by dairy cows when the dry matter intake of a 1:1-ratio of grass silage and concentrate diet was increased from 10 to 24 kg per day. Although CH<sub>4</sub> production increases almost linearly with a higher feed intake, the fraction of consumed GE lost as CH<sub>4</sub> reduces. This effect is partly a consequence of a reduction in lower rumen digestibility with increased feed intake (factor 1), and partly a consequence of shifts in the rumen fermentation pattern and the type of VFA produced (factor 2).

**2.1.1.2. Factor 2.** Bannink et al. (2000), recently updated coefficients for the production of VFA from different types of substrate fermented in the rumen of specifically lactating cows. With these new coefficients, Mills et al. (2001) demonstrated that replacing sugars by starch in concentrate reduced the total CH<sub>4</sub> production by 14.7%. Also, the rate of fermentation of OM in the rumen (see Section 2.1.1.1) is known to affect the type of VFA produced. When the production rates rise and rumen pH drops, a shift occurs towards more production of propionate, mainly because of shifts in the abundance of species of micro-organisms present in the gastrointestinal tract. As an alternative to the production of CH<sub>4</sub>, also propionate acts as a sink of [H] and consequently less CH<sub>4</sub> will be produced per unit of OM fermented (Pitt et al., 1996; Baldwin, 1995). Since high-yielding cows have a higher intake of dry matter (which is to be expected to result in low rumen pH), the effect of increasing the starch content of the diet on CH<sub>4</sub> production is expected to be even larger.

**2.1.1.3. Factor 3.** Current feed evaluation systems assume a rather constant figure for the efficiency of microbial synthesis (e.g. 150 g of protein per kg of OM fermented; Dutch protein evaluation system). However, Dijkstra et al. (1992) demonstrated that environmental conditions in the rumen have a major impact on this efficiency. Hence, dietary measures and their consequences for rumen fermentation conditions may also have a large impact on the efficiency of microbial growth achieved and, consequently, on the quantities of OM converted into VFA and CH<sub>4</sub> produced. Although microbial biosynthesis also acts as a sink or source of [H], depending on ammonia or amino acids used as a nitrogen source (Benchaar et al., 1998; Mills et al., 2001), this affects rumen [H] balance much less than the type of VFA produced (factor 2) and the quantity of OM converted into VFA (factors 1 and 3 combined). For reviews on the matter the reader is referred to Bannink and De Visser (1997) and Dijkstra et al. (1996).

The above factors are also relevant to digestion in monogastric animals (e.g. pigs), although normally most of the feed ingested will be digested enzymatically instead of fermentatively. Only in the large intestine fermentation

Table 1

Typical absolute and relative CH<sub>4</sub> emissions from enteric fermentation and manure (Monteny et al., 2001)

	Total (kg CH <sub>4</sub> per year per animal)	Contribution of enteric fermentation (%)
Dairy cows	84–123	75–83
Pigs	4.8	30
Poultry	0.26	~0

(flatus) CH<sub>4</sub> production becomes substantial, in particular when carbohydrates fed are enzymatically indegradable and therefore end up undegraded in the large intestine. Although the precise fermentation conditions in the large intestine will be different from those in the rumen, the same principles of microbial fermentation and CH<sub>4</sub> production hold. Bakker (1996) found, in experiments with pigs (maize starch replacement by products with a high content of fermentable carbohydrates), that some 10% of the GE digested in the large intestine was retrieved as CH<sub>4</sub>, ranging from 0.5 to 1.9% of GE consumed. Therefore, the digestive process in pigs generates at the most 1/3 (up to 2% of GE intake) of the CH<sub>4</sub> produced in ruminants (up to 7% of GE intake; Pelchen et al., 1998; IPCC, 1997; Mills et al., 2001), but it may still be considered substantial when diets with a high content of fermentable carbohydrates instead of starch-rich feed ingredients are fed.

### 2.1.2. Animal manure

Fermentation of manure (digestion), both solid and liquid, is an anaerobic process (absence of oxygen). It has some similarities with enteric fermentation, and is described in detail, e.g. by Burton (1997) and Møller (2001). In brief, the fermentation process runs in two steps:

- (a) Fast growth of acidogenic bacteria, active in a wide temperature range (3–70 °C) with an optimum at 30 °C. Intensive mixing of substrate and bacteria producing organic acids, [H], and CO<sub>2</sub>.
- (b) Specific methanogenic bacteria (psychrophilic, <20 °C; mesophilic, 20–40 °C; thermophilic, >40 °C) produce CH<sub>4</sub> from organic acids.

Methane production from animal manure (also known as biogas) increases with temperature, and with increased biodegradability of the manure (or the combination of manure and by-products; see e.g. Wulf et al., 2005). Although digestion at higher temperatures generates more CH<sub>4</sub>, the costs of energy needed for additional heating have to be considered in the choice of the optimal reactor. The quality of the substrate greatly determines CH<sub>4</sub> production. Specific pH values and carbon:nitrogen ratios (optimum is between 13:1 and 28:1) have to be realized. Since digestion of animal manure is a biological process, the concentrations of inhibitory compounds like ammonia/ammonium and sulphides need to be kept low when optimal gas production is envisaged.

### 2.2. Nitrous oxide

The main sources of N<sub>2</sub>O are nitrogen fertiliser and animal manure applications to land, and urine deposition by grazing animals (Brown et al., 2001), although it also may be released in deep litter systems and from solid manure heaps (Chadwick et al., 1999). Even silage clamps may be a source of N<sub>2</sub>O. Whereas, CH<sub>4</sub> is commonly produced from animal

manures, N<sub>2</sub>O production only takes place under specific conditions since it results from combined aerobic and anaerobic processes:

- (a) nitrification: transformation of ammonium to nitrate (aerobic);
- (b) denitrification: formation of nitrogen gas from nitrate reduction (anaerobic).

As a consequence, N<sub>2</sub>O emission is influenced by the environmental factors oxygen status, temperature, moisture content and antecedent soil conditions, which control enzyme production. Normally, conditions in manure are strictly anaerobic, and processes (a) and (b) will not occur. However, when forced and controlled aeration of liquid manure ('aerobic treatment') or solid manure ('composting') is used to achieve removal of OM and nitrogen, and water (drying), respectively, denitrification occurs after aeration. Besides these examples of active nitrification/denitrification, the processes (a) and (b) also happen in a situation of passive aeration, e.g. in organic housing systems and systems with enhanced animal welfare where straw or litter may be introduced. The mixture of manure and straw/litter, combined with (partial) compaction of the bedding creates conditions that favor passive aeration, resulting in uncontrolled nitrification and denitrification (Groenestein and Van Faassen, 1996). Although ammonia emissions from these types of housing systems are usually reduced, there is a significant trade off to N<sub>2</sub>O (and CH<sub>4</sub>), resulting in a net higher N-emission than observed from traditional, liquid manure based, housing systems.

## 3. Mitigation options

### 3.1. Methane

Methane emission per unit of animal product will be reduced by any process that increases the ratio of livestock 'production' to 'maintenance'. Thus faster growth, higher milk yields and shorter dry periods in lactating cows will lower CH<sub>4</sub> emissions. Likewise, an increase in the average longevity of dairy cows (i.e. a greater number of lactations per lifetime) relative to the period from birth to first calving (usually 3 years) will reduce CH<sub>4</sub> loss per unit of milk yield. Additionally, measures concerning technology (e.g. aerobic digestion) and management based solutions may be implemented (Harrison et al., 2003). However, only mitigations that involve a reduction in the number of animals would currently register as a reduction in the IPCC inventory (IPCC, 1997) because this is based on a standard emission factor. Other forms of mitigation, for example those based on manipulation of the diet, could produce 'real' reductions in CH<sub>4</sub> production, but presently these would go unrecorded in the inventory, unless they indirectly led to a reduction in livestock numbers.

### 3.1.1. Dietary measures

It is widely recognized that alterations in the diet strongly affect rumen functioning and the performance of ruminants (e.g. roughage:concentrate ratio, or the fibre, starch, sugars and protein content of the feed). Similarly, dietary composition may strongly affect the supply and subsequent fermentation of substrate in the large intestine of pigs as well as ruminants (quantity of and type of starch, fibre and protein inflow to large intestine). In particular, the fermentative capacity of the large intestine of pigs is excessive, whereas, it is considered minor in ruminants in comparison to that of the rumen. Changes in feeding strategy or farm management may have a large impact on GHG production by farm animals. Concerning ruminants, the most effective measures are (in theory):

- (a) increase the level of starch or rapidly fermentable carbohydrates (soluble carbohydrates and starch in concentrates), to enhance propionate production, reduce excess [H] and subsequent CH<sub>4</sub> formation;
- (b) alter the diet concerning feed intake and feed composition to allow for a higher animal productivity;
- (c) reduce [H] by addition of (unsaturated) fat or stimulation of acetogenic bacteria;
- (d) reduction of methanogens or removal of protozoa (through additives or probiotics).

In practice, only (a) and (b) seem feasible and applicable in today farming practices. Options (c) (Sauer et al., 1998) and (d) are either purely theoretical, under study (cf. Machmüller, this issue) or may encounter resistance from consumers (especially (d)). Mills et al. (2001) demonstrated that changing from an intensive system with less cows fed ad libitum (9150 kg of 305 days milk yield) to an extensive system with restricted feeding of more cows (6100 kg of 305 days milk yield) reduced CH<sub>4</sub> production per cow per day with 20%, yet a 21% increase of the CH<sub>4</sub> production of the total herd was observed. This study illustrated that an evaluation of dietary measures at the farm level requires first of all a careful evaluation at the animal (or even rumen) level, and subsequently an evaluation at the herd level in terms of herd productivity, nutrient utilization, costs, and similar characteristics that are important at the farm level.

### 3.1.2. Housing and storage

Methane is poorly soluble in water. This implies that produced CH<sub>4</sub> will instantly emit to the air inside the house. Hence, possible options to reduce emissions from the house and (indoor) storage have to focus on:

- (a) reduction of gas production through deep cooling of manure (<10 °C) or a substantial reduction of manure pH, e.g. via additives;
- (b) removal of the gas source, e.g. by frequently and completely removing manure from indoor storage pits;

- (c) proper management of the bedding and manure heaps, e.g. minimize compaction, frequent addition of straw/litter, regular removal.

Option (a) requires additional equipment to extract heat from the manure or to apply the additives. Sommer et al. (2004) showed that cooling of pig slurry in-house reduced CH<sub>4</sub> (and N<sub>2</sub>O) emissions with 21% relative to not cooling. Furthermore, additives like lactic acid (Berg and Pazsiczki, 2003) and lime-stone can result in even further reductions (up to 80%). Frequent and complete removal of the manure from the pits (option (b); Osada et al., 1998) is effective, but will only be feasible (and effective) in situations with sufficient outdoor storage capacity and additional measures to prevent CH<sub>4</sub> emissions to occur outdoors. Anaerobic digestion (biogas production), flaring/burning (chemical oxidation; burning) or special biofilters (biological oxidation; Melse, 2003) can be operated. Biogas production (reviewed by Burton, 1997, and by Burton and Turner, 2003), combined with on-farm power/heat generation, seems the most logical measure. Its feasibility will mainly depend on the energy prize (use on own farm, delivering electricity to the public net) and on possibilities (or restrictions) to co-digest waste products to increase gas production (see Nielsen and Hjort-Gregersen, 2005).

Proper management of bedding material (indoor; Groenestein and Van Faassen, 1996) and manure heaps (outdoor) will reduce GHG emissions, since substantial amounts of CH<sub>4</sub> and N<sub>2</sub>O are produced under sub-optimal conditions (Hüther et al., 1997).

## 3.2. Nitrous oxide

Options to reduce N<sub>2</sub>O emissions from specific sources have been identified and tested to various degrees. In a recent review of greenhouse gas emissions from agriculture in the UK, Harrison et al. (2003) concluded that the most effective potential specific options are: (1) choice of fertiliser form, (2) nitrification inhibitors, (3) land drainage management, (4) storage of solid manure, (5) N<sub>2</sub>O:N<sub>2</sub> ratio, and (6) housing systems and management.

### 3.2.1. Choice of fertiliser form

Fertiliser type is thought to influence N<sub>2</sub>O emissions, with nitrate-based fertilisers resulting in greater emission factors than ammonium-based fertilisers. For example, a review conducted by Eichner (1990) suggested that the average emission factor for ammonium nitrate was 0.44% whilst that for urea was 0.11% of the N applied. In a more recent experimental study, Dobbie and Smith (2003a) compared N<sub>2</sub>O emissions from various fertiliser types with and without various inhibitors (nitrification and urease). Their results demonstrated that the use of urea on grassland in spring reduced N<sub>2</sub>O emissions compared to the use of ammonium nitrate (Dobbie and Smith, 2003a) in both years. Application of a different fertiliser form, e.g. urea instead of

ammonium nitrate, would have no extra cost and may even be cheaper to purchase. Slow release fertilisers have been formulated to help synchronise N release with plant growth. Theoretically, it should be possible to provide sufficient nitrogen to satisfy plant requirements in only one application and maintain low soil mineral N concentrations throughout the growing season. The result being that N<sub>2</sub>O emissions will be limited by the small soil mineral N pool. Indeed, Smith et al. (1997) showed that N<sub>2</sub>O emissions were significantly reduced following application of a coated slow release ammonium nitrate based and coated slow release ammonium sulphate based fertiliser compared to uncoated fertiliser nitrogen.

### 3.2.2. Addition of a nitrification inhibitor

Nitrification inhibitors (NIs) can be added to urea or ammonium compounds. In the study by Dobbie and Smith (2003a) the use of a NI with urea fertilisers reduced N<sub>2</sub>O emissions compared to urea alone. Nitrapyrin, dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) have well-demonstrated effectiveness for lowering N<sub>2</sub>O emissions from fertiliser and animal slurries (Pain et al., 1994). Dittert et al. (2001) demonstrated a win–win scenario using DMPP additions to dairy slurry.

Slurry injection is known to significantly decrease ammonia emissions compared with surface spreading (Misselbrook et al., 2002), but injection can result in increased N<sub>2</sub>O emissions (Chadwick et al., 1999). Dittert et al. (2001) found that the N<sub>2</sub>O emissions from slurry treated with DMPP were 32% lower than from non-treated slurry when injected into grassland, and the use of <sup>15</sup>N label confirmed that this reduction was from slurry derived N<sub>2</sub>O. Ammonia emissions were negligible.

There is also the potential to use NIs on grazing land. This is an approach that is being adopted in New Zealand in order to reduce the N<sub>2</sub>O emissions from urine deposition (Di and Cameron, 2003). The two main fertilizer manufacturers, Ravensdown (<http://www.ravensdown.co.nz/products/national2005/specialist.htm> (date of access: 13 July 2005)) and Ballance AgriNutrients (<http://www.ballance.co.nz/unewsapr07-05.html> (date of access: 13 July 2005)) each have their own NI product: Eco-N and N-care, respectively. Eco-N is a finer product that is suspended in solution and then irrigated onto pasture, while N-care is a solid product that is mixed with urea fertilizer and then broadcast onto pasture. The rationale behind Eco-N is that it not only will be effective on fertilizer but also on urinary N as it is sprayed onto pasture. Costs of NIs may be offset by increased efficiency. The degree of uptake of NI use may depend on the public's perception of introducing another chemical into the environment.

### 3.2.3. Land drainage

There is a well documented relationship between N<sub>2</sub>O emissions and water filled pore space whereby water filled pore space of more than 70% results in significant N<sub>2</sub>O

emissions (Maag, 1990; Dobbie and Smith, 2003b). Therefore, improvement of soil physical conditions to reduce soil wetness, especially in grassland systems, may significantly reduce N<sub>2</sub>O emissions. For example, neglect of land drainage in the UK since the cessation of subsidies means that soil aeration status has been gradually deteriorating. Improving drainage would be particularly beneficial on grazed grassland. Soil compaction by traffic, tillage and grazing livestock can increase the anaerobicity of the soil and enhance conditions for denitrification. It is thought that treading by cattle could increase emissions of N<sub>2</sub>O by a factor of two (Oenema et al., 1997). Clark et al. (2001) suggested that by avoiding compaction, the total national N<sub>2</sub>O emission (for 1998) could be reduced by 3%.

### 3.2.4. Solid manure stores

Specific N<sub>2</sub>O mitigation options from solid manure heaps include the addition of high C substrate. Also, compaction of solid manure heaps to reduce oxygen entering the heap and maintaining anaerobic conditions has had mixed success in reducing N<sub>2</sub>O emissions (Chadwick, unpublished). In contrast, one would expect CH<sub>4</sub> emissions to be increased following compaction of heaps, i.e. a case of swapping one form of pollutant for another.

### 3.2.5. N<sub>2</sub>O:N<sub>2</sub> ratio

Nitrous oxide is one of the products of nitrification (Bremner and Blackmer, 1978), whilst both nitrogen gas (N<sub>2</sub>) and N<sub>2</sub>O are products of denitrification (Firestone and Davidson, 1989). Increased knowledge of the factors controlling the N<sub>2</sub>O:N<sub>2</sub> ratio could be used to inform management practices that may lead to a greater proportional flux of N<sub>2</sub> (compared to N<sub>2</sub>O). Carbon quality is known to influence the ratio of N<sub>2</sub>O:N<sub>2</sub> (Paul et al., 1993). Hence, an improved understanding of the influence of anaerobic digestion and storage of slurry on C quality at the time of manure application may result in improved management practices to reduce N<sub>2</sub>O emissions.

Amon et al. (2002) showed that the N<sub>2</sub>O emissions from slurry applications to grassland were reduced when slurry had been stored for 6 months or had passed through an anaerobic digester prior to spreading in comparison to fresh slurry. The inference being that during storage and anaerobic digestion readily available C (that could be used to fuel denitrification) is incorporated into microbial biomass or lost as CO<sub>2</sub> or CH<sub>4</sub>, hence there is less available C in the slurry to fuel denitrification when the slurry is applied to land. Indeed anaerobic digestion is potentially a 'win–win' management of animal slurry, since CH<sub>4</sub> emitted during storage (as biogas) is used to produce heat and electricity, whilst N<sub>2</sub>O emissions following the spreading of the digested slurry are also reduced (see for example, Clemens et al., 2005).

### 3.2.6. Housing system and management

The choice of manure management and housing system will influence greenhouse gas emissions, particularly N<sub>2</sub>O.

Changes of practice, e.g. for reasons of animal welfare, may increase straw use and hence the production of solid farm yard manure (FYM). Animal housing and manure stores of straw-based systems (deep litter) will result in greater N<sub>2</sub>O emissions than the more anaerobic slurry-based systems (Thorman et al., 2003; Groenestein and Van Faassen, 1996). So, a management change from straw- to slurry-based systems may result in lower N<sub>2</sub>O emissions.

Some dairy and beef farmers are extending the grazing season to reduce feed costs and labour. This will in general not affect CH<sub>4</sub> emissions, but it may increase the risk of N<sub>2</sub>O emissions and nitrate leaching. Minimising the grazing period is likely to reduce N<sub>2</sub>O emissions, since the more uniform return of excreta via slurry spreading results in lower emissions than from urine deposited by grazing animals (Oenema et al., this issue).

#### 4. Interactions with other policies

There are important interactions between mitigation measures for gaseous emissions and nitrate leaching (risk of pollution swapping), so mitigation practices need to be evaluated at the system level (i.e. holistically). Brink et al. (2001) indicated that NH<sub>3</sub> abatement will result in a 15% lower emission of N<sub>2</sub>O, mainly due to adaptations in animal houses and low emission manure application techniques. Also reversed interactions are observed. A move from straw based cattle housing systems to slurry-based systems to reduce N<sub>2</sub>O emissions would result in increased ammonia emissions (Chambers et al., 2002). The mitigation strategies for N<sub>2</sub>O may have effects on other policy issues: e.g. substituting urea for ammonium nitrate would increase NH<sub>3</sub> emissions (Misselbrook et al., 2000). Improving land drainage may increase NO<sub>3</sub><sup>-</sup> leaching, both of which would also result in increased indirect N<sub>2</sub>O emissions. Policies relating to nitrate vulnerable zones (NVZs) will result in more organic manures being spread during the growing season, so the interaction between manure and fertiliser nitrate on N<sub>2</sub>O emissions may be important. Slurry applied at the same time as fertiliser nitrate increases N<sub>2</sub>O emission, with up to 5% of the NO<sub>3</sub><sup>-</sup>-N being lost as N<sub>2</sub>O (Stevens and Laughlin, 2001, 2002). Microbial degradation of organic C in slurries should be allowed to occur for a few days in the soil before applying nitrate-containing fertiliser.

Mitigation strategies for NH<sub>3</sub> in animal husbandry were found to have no effect on CH<sub>4</sub> emissions (Brink et al., 2001). This is mainly because the N- and C-cycles in agriculture are only integrated to some extent and consequently pathways for mitigation differ. Methane emission reduction options have to be based upon animal nutrition (enteric fermentation) and manure management inside or outside the animal houses. Because of the potential of CH<sub>4</sub> for energy production, the on-farm production and use of biogas through anaerobic digestion as a fuel serves the climate change problem from both reduced emissions of

CH<sub>4</sub> and CO<sub>2</sub> (from fossil fuels). Moreover, anaerobic digestion results in a manure product with an increased amount of NH<sub>3</sub>, that is readily available for plant uptake, available C, with may reduce N<sub>2</sub>O emissions after land spreading. Furthermore, the odour (smell) is reduced due to degradation of VFA in manure, which results in a reduced nuisance.

#### 5. Conclusions

Agriculture in general, and livestock production in particular, contribute to global warming through emissions of the non-CO<sub>2</sub> GHGs CH<sub>4</sub> and N<sub>2</sub>O. Most CH<sub>4</sub> is emitted from ruminants (animal + manure), whereas, N<sub>2</sub>O is mainly emitted from fertilized land.

Methane mitigation options from ruminants focus on increasing production per animal, modifying diet, decreasing numbers of methanogens and methanogen activity and by reducing livestock numbers. Manure related CH<sub>4</sub> can be reduced by minimizing uncontrolled storage (indoors). Controlled storage offers possibilities for utilization of CH<sub>4</sub> produced (biogas).

Nitrous oxide mitigation options include better N use (from fertilisers and manures), land drainage, use of nitrification inhibitors. Mitigation of N<sub>2</sub>O from solid manure heaps could be achieved through the use of high C additives and compaction. Anaerobic digestion of slurries can be used to (a) directly reduce CH<sub>4</sub> emissions through biogas generation (heat and energy production) and (b) indirectly reduce N<sub>2</sub>O emissions when slurries are applied to land by decreasing the readily available C content.

It is essential that GHG mitigation options take other policies into account, e.g. the requirement to reduce NO<sub>3</sub><sup>-</sup> leaching and NH<sub>3</sub> volatilisation. It should be noted that, a reduction in the amount of fertiliser N used through more efficient use, e.g. by timing applications and rates to crop requirements, as well as an integrated approach to the use of animal manures with fertilisers to supply N for crop growth should reduce the risk of excess mineral N remaining in the soil at risk of loss as N<sub>2</sub>O. Such improvement in fertiliser and manure management would play an important role in reducing not only N<sub>2</sub>O emissions but also other losses of N, e.g. as ammonia and nitrate.

#### Web-sites:

<http://www.ballance.co.nz/unewsapr07-05.html> (date of access: 13 July 2005).

<http://www.ravensdown.co.nz/products/national2005/specialist.htm> (date of access: 13 July 2005).

#### References

- Amon, B., Moitzi, G., Schimpl, M., Kryvoruchko, V., Wagner-alt, C., 2002. Methane, Nitrous Oxide and Ammonia Emissions from Management of

- Liquid Manures, Final Report 2002. On behalf of Federal Ministry of Agriculture, Forestry, Environmental and Water Management “and” Federal Ministry of Education, Science and Culture Research Project No. 1107, BMLF GZ 24.002/24-IIA1a/98 and Extension GZ 24.002/33-IIA1a/00.
- Bakker, G.C.M., 1996. Interaction Between Carbohydrates and Fat in Pigs. Impact on Energy Evaluation in Feeds. PhD Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, 193 p. (see: <http://library.wur.nl/way/>).
- Baldwin, R.L., 1995. Modeling Ruminant Digestion and Metabolism. Chapman & Hall, London: UK, 578 p.
- Bannink, A., Kogut, J., Dijkstra, J., France, J., Tamminga, S., Van Vuuren, A.M., 2000. Modelling production and portal appearance of volatile fatty acids in cows. In: McNamara, J.P., France, J., Beaver, D.E. (Eds.), Modelling Nutrient Utilization in Farm Animals. CAB International, Wallingford, United Kingdom, pp. 87–102.
- Bannink, A., De Visser, H., 1997. Comparison of mechanistic rumen models on mathematical formulation of extramicrobial and microbial processes. *J. Dairy Sci.* 80, 1296–1314.
- Benchaar, C.J., Rivest, J., Pomar, C., Chiquette, J., 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. *J. Anim. Sci.* 76, 617–627.
- Berg, W., Pazzicchi, I., 2003. Reducing emissions by combining slurry covering and acidification. In: Pedersen, et al. (Eds.), Proceedings of the International Symposium on Gaseous and odour emissions from animal production facilities, Horsens, Denmark, 1–4 June 2003, pp. 460–468.
- Bremner, J.M., Blackmer, S.M., 1978. Nitrous oxide: emission from soils during nitrification of fertiliser nitrogen. *Science* 199, 295–296.
- Brink, C., Kroeze, K., Klimont, Z., 2001. Ammonia abatement and its impact on emissions of nitrous oxide and methane. Part 2. Application for Europe. *Atmos. Environ.* 35 (36), 6313–6325.
- Brown, L., Armstrong Brown, S., Jarvis, S.C., Syed, B., Goulding, K.W.T., Phillips, V.R., Sneath, R.W., Pain, B.F., 2001. An inventory of nitrous oxide emissions from agriculture in the UK using the IPCC methodology: emission estimate, uncertainty and sensitivity analysis. *Atmos. Environ.* 35, 1439–1449.
- Burton, C.H., 1997. Manure Management: Treatment Strategies for Sustainable Agriculture. Silsoe Research Institute, Bedford, UK, 181 pp.
- Burton, C.H., Turner, C., 2003. Manure Management: Treatment Strategies for Sustainable Agriculture, 2nd ed. Silsoe Research Institute, Bedford, UK, 451 pp.
- Chadwick, D.R., Sneath, R.W., Phillips, V.R., Pain, B.F., 1999. A UK inventory of nitrous oxide emissions from farmed livestock. *Atmos. Environ.* 33, 3345–3354.
- Chambers, B.J., Williams, J.R., Cooke, S.D., Kay, R.M., Chadwick, D.R., Balsdon, S.L., 2002. Ammonia emissions from contrasting cattle and pig manure management systems. In: McTaggart, I., Gairns, L. (Eds.), Proceedings of SAC/SEPA Conference on Agriculture, Waste and the Environment, Edinburgh 26–28 March 2002, pp. 19–25.
- Clark, H., de Klein, C.A.M., Newton, P., 2001. Potential Management Practices and Technologies to Reduce Nitrous Oxide, Methane and Carbon Dioxide Emissions from New Zealand Agriculture. Report prepared for MAF, September 2001.
- Clemens, J., Trimborn, M., Weiland, P., Amon, B., 2005. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agric. Ecosys. Environ.* (this issue).
- Di, H.J., Cameron, K.C., 2003. Mitigation of nitrous oxide emissions in spray-irrigated grazed grassland by treating the soil with dicyandiamide, a nitrification inhibitor. *Soil Use Manage.* 19, 284–290.
- Dijkstra, J., St. Neal, H.D., Beaver, D.E., France, J., 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: model description. *J. Nutr.* 122, 2239–2256.
- Dijkstra, J., France, J., Sauvant, D., 1996. A comparative evaluation of models of whole rumen function. *Annales de Zootechnie* 45 (Suppl. 1), 175–192.
- Dittert, K., Bol, R., King, R., Chadwick, D., Hatch, D., 2001. Use of a novel nitrification inhibitor to reduce nitrous oxide emissions from <sup>15</sup>N labelled dairy slurry injected into the soil. *Rapid Commun. Mass Spec.* 15, 1291–1296.
- Dobbie, K.E., Smith, K.A., 2003a. Impact of different forms of N fertilizer on N<sub>2</sub>O emissions from intensive grassland. *Nutr. Cycling Agroecosyst.* 67, 37–46.
- Dobbie, K.E., Smith, K.A., 2003b. Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. *Global Change Biol.* 9, 204–218.
- Eichner, M.J., 1990. Nitrous oxide emissions from fertilized soils: a summary of available data. *J. Environ. Qual.* 19, 272–280.
- Firestone, M.K., Davidson, E.A., 1989. Microbial basis of NO and N<sub>2</sub>O production and consumption in soil. In: Andreae, M.O., Schimel, D.S. (Eds.), Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. Wiley, New York, pp. 7–21.
- Freibauer, A., Kaltschmitt, M., 2001. Biogenic Greenhouse Gas Emissions from Agriculture in Europe. *Forschungsbericht* 78, University of Stuttgart, IER, 220 pp.
- Groenestein, C.M., Van Faassen, H.G., 1996. Volatilization of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs. *J. Agric. Eng. Res.* 65, 269–274.
- Groot Koerkamp, P.W.G., Uenk, G.H., 1997. Climatic conditions and aerial pollutants in and emissions from commercial production systems in the Netherlands. In: Voermans, J.A.M., Monteny, G.J. (Eds.), Proceedings of the International Symposium on Ammonia and Odour Control from Animal Production Facilities. Research Station for Pig Husbandry (PV), Rosmalen, pp. 139–144.
- Harrison, R., Moss, A., Stevens, J., Thomas, P.C., 2003. Reducing Greenhouse Gases from Agriculture. Final Project Report (CC0260). UK Department of Environment Food and Rural Affairs (DEFRA), 50 pp.
- Husted, S., 1994. Seasonal variation in methane emission from stired slurry and solid manures. *J. Environ. Qual.* 23, 585–592.
- Hüther, L., Schuchardt, F., Willke, T., 1997. Emissions of ammonia and greenhouse gases during storage and composting of animal manures. In: Voermans, J.A.M., Monteny, G.J. (Eds.), Proceedings of the International Symposium on Ammonia and odour control from animal production facilities. Research Station for Pig Husbandry (PV), Rosmalen, pp. 327–334.
- IPCC, 1997. IPCC Revised 1996 Guidelines for National Greenhouse Gas Inventories, vol. 3, Greenhouse Gas Inventory Reference Manual. IPCC WGI Technical Support Unit, Hadley Centre, Meteorological Office, Bracknell.
- IPCC, 2001. In: Houghton, J.T., et al. (Eds.), Climate Change 2001: The Scientific Background, vol. 94. Cambridge University Press, Cambridge, UK.
- Maag, M., 1990. N<sub>2</sub>O production rates and denitrification rates on soil amended with pig slurry. *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft* 60, 205–210.
- Melse, R. 2003. Personal communication.
- Mills, J.A.N., Dijkstra, J., Bannink, A., Cammell, S.B., Kebreab, E., France, J., 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating cow: model development, evaluation, and application. *J. Anim. Sci.* 79, 1584–1597.
- Misselbrook, T.H., Van der Weerden, T.J., Pain, B.F., Jarvis, S.C., Chambers, B.J., Smith, K.A., Phillips, V.R., Demmers, T.G.M., 2000. Ammonia emissions factors for UK agriculture. *Atmos. Environ.* 34, 871–880.
- Misselbrook, T.H., Smith, K.A., Johnson, R.A., Pain, B.F., 2002. Slurry application techniques to reduce ammonia emissions: results of some UK field-scale experiments. *Biosyst. Eng.* 81, 313–321.
- Møller, H.B., 2001. Anaerobic Digestion and Separation of Livestock Slurries. Danish Experiences. Manuscript for Matresa, 2nd ed. Danish Institute of Agricultural Sciences, Research Centre Bygholm, Horsens, Denmark.
- Monteny, G.J., Groenestein, C.M., Hilhorst, M.A., 2001. Interaction and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutr. Cycl. Agroecosyst.* 60, 123–132.

- Nielsen, L.H., Hjørt-Gregersen, K., 2005. Greenhouse gas emission reduction via centralized biogas co-digestion plants in Denmark. *Agric. Ecosys. Environ.* (this issue).
- Oenema, O., Velthof, G.L., Yamulki, S., Jarvis, S.C., Smith, K., 1997. Nitrous oxide emissions from grazed grassland. *Soils and the greenhouse effect. Soil Use Manage.* 13, 288–295.
- Osada, T., Rom, H.B., Dahl, P., 1998. Continuous measurement of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. *Trans. ASAE* 41, 1109–1114.
- Pain, B.F., Misselbrook, T.H., Rees, Y.J., 1994. Effects of nitrification inhibitor and acid addition to cattle slurry following the surface application or injection to grassland. *Grass Forage Sci.* 49, 209–215.
- Paul, J.W., Beauchamp, E.G., Zhang, X., 1993. Nitrous oxide and nitric oxide emissions during nitrification and denitrification from manure-amended soil in the laboratory. *Can. J. Soil Sci.* 73, 539–553.
- Pelchen, A., Peters, K.J., Holter, J.B., 1998. Prediction of methane emissions from lactating dairy cows. *Arch. Tierz. Dummerstorf* 41, 553–563.
- Pitt, R.E., Van Kessel, J.S., Fox, D.G., Pell, A.N., Barry, M.C., Van Soest, P.J., 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. *J. Anim. Sci.* 74, 226–244.
- Sauer, F.D., Fellner, V., Kinsman, R., Kramer, J.K.G., Jackson, H.A., Lee, A.J., Chen, S., 1998. Methane output and lactation response in Holstein cattle with momensin or unsaturated fat added to the diet. *J. Anim. Sci.* 76, 906–914.
- Sommer, S.G., Petersen, S.O., Møller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutr. Cycl. Agroecosyst.* 69, 143–154.
- Smith, K.A., McTaggart, I.P., Tsuruta, H., 1997. Emissions of N<sub>2</sub>O and NO associated with nitrogen fertilisation in intensive agriculture, and the potential for mitigation. *Soil Use Manage.* 13, 296–304.
- Stevens, R.J., Laughlin, R.J., 2001. Cattle slurry affects nitrous oxide and dinitrogen emissions from fertiliser nitrate. *Soil Sci. Soc. Am. J.* 65, 1307–1314.
- Stevens, R.J., Laughlin, R.J., 2002. Cattle slurry applied before fertilizer nitrate lowers nitrous oxide and dinitrogen emissions. *Soil Sci. Soc. Am. J.* 66, 647–652.
- Thorman, R., Harrison, R., Cooke, S.D., Ellis, S., Chadwick, D.R., Burston, M., Balsdon, S.L., 2003. Nitrous oxide emissions from slurry- and straw-based systems for cattle and pigs in relation to emissions of ammonia. In: McTaggart, I., Gairns, L. (Eds.), *Proceedings of SAC/SEPA Conference on Agriculture, Waste and the Environment*, Edinburgh, 26–28 March 2002, pp. 26–32.
- Wulf, S., Jäger, P., Döhler, H., 2005. Balancing of greenhouse gas emissions and economic efficiency for biogas-production through anaerobic co-fermentation of slurry with organic waste. *Agric. Ecosys. Environ.* (this issue).