BIOCAP Canada Foundation
Queen's University
156 Barrie Street, Kingstion, Ontario Canada K7L 3N6
Tel. 613-542-0025 Fax. 613-542-0045 E-mail: info@biocap.ca Website: www.biocap.ca

Discussion Paper for the 2nd Meeting of the Animal Production and Manure Management Network

Supporting Measurements Required for Evaluation of Greenhouse Gas Emission Models for Enteric Fermentation and Stored Animal Manure

C. Wagner-Riddle[1], E. Kebreab[2], J. France[2], K. Clark[1], and J. Rapai[1]

[1] *Department of Land Resource Science,* [2] *Centre for Nutrition Modelling, Department of Animal and Poultry Science, University of Guelph, Guelph, Ontario N1G 2W1, Canada*

1 Abstract

Emissions of methane and nitrous oxide, which enhance the atmospheric greenhouse effect, occur at several stages of the animal production system. Additional research is required in order to understand these emissions, and to quantify potential reduction measures. The usefulness of future emission data obtained can be maximized if supporting measurements are carried out. These data include feed intake (amount, components, degradabilities), animal numbers, weight and physiological state; nitrogen and carbon excretion (amount and forms); characteristics of manure handling system (eg. manure composition, dimensions of storage); environmental conditions of manure storage.

2 Introduction

The potential environmental impact of animal production is wide ranging comprising aspects of human health, water, soil, and air quality. Recently, concerns with increased atmospheric concentration of gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and the related enhancement of the greenhouse effect, have prompted calls for quantification and better understanding of greenhouse gas (GHG) emissions related to animal production. These emissions occur in the form of CH_4 and N_2O at several stages of the animal-manure-soil-crop (AMSC) continuum, and are a function of the carbon and nitrogen transfer between compartments, starting with animal feed intake, and ending with nutrient uptake by crops (Figure 1).

Limited data on GHG emissions associated with animal production are available worldwide (NRC, 2003). Efforts to address this research gap have focussed on individual components of the AMSC continuum, but, clearly, effective management of GHG emissions require an understanding of the whole nutrient cycle. Most animal nutrition and enteric fermentation studies have not been concerned with GHG emissions 'downstream' from the 'animal' compartment (Figure 1). Likewise, studies on GHG emissions during storage or treatment of manure and after manure application are often carried out outside an animal nutrition context. Hence, the usefulness of emission data obtained is compromised, in particular, for future efforts on modelling of GHG for the AMSC continuum.

The objectives of this paper are to: 1) briefly review processes and controlling factors involved in GHG production and emission associated with animal production; 2) review currently used models that describe GHG emissions from animal production; and 3) identify supporting measurements and reporting standards for GHG emission studies to improve the usefulness of obtained data. In our discussion we will first address these objectives for methane emissions from enteric fermentation, and then for methane and nitrous oxide emissions from manure storage.

3 Methane Emissions from Enteric Fermentation

3.1 Processes and Controlling Factors

About 90% of CH_4 emissions from enteric fermentation in Canada (19 Mt CO_2-equivalent, 3% of total GHG emissions) originate from ruminants (Matin et al., 2004). Enteric CH_4

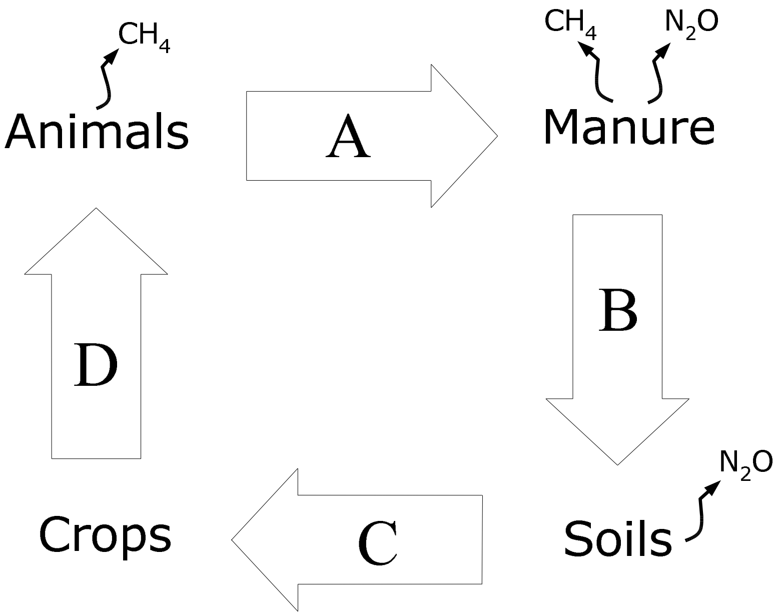

Figure 1: Transfer of nitrogen and carbon in animal production systems from animals to manure storage in the form of feces and urine(A), from manure storage to soils through field application of manure (B), from soils to crops through plant uptake (C), and from crops or pasture to animals through feed intake (D). Potential emissions of greenhouse gases, methane and mitrous oxide, are shown for each compartment of the cycle

production arises principally from microbial fermentation of hydrolysed dietary carbohydrates such as cellulose, hemicellulose, pectin and starch. The primary substrates for ruminal methanogenesis are hydrogen (H_2) and CO_2. Most of the H_2 produced during fermentation of hydrolysed dietary carbohydrates, much of which is generated during the conversion of hexose to acetate or butyrate via pyruvate, ends up in CH_4. Significant quantities of ruminal CH_4, particularly with high-protein diets, can also arise from microbial fermentation of amino acids, the end-products of which are ammonia, volatile fatty acids (VFA), CO_2 and CH_4 (Mills et al., 2001). The environmental consequences aside, methane emissions represent an energetic inefficiency that impacts on profitability of livestock production through reduced feed conversion efficiency. Therefore, the rationale of the producers and the policy makers may be different but the goal of reduced emissions is universal.

The amount of CH_4 produced by an animal is influenced by many factors. These include dietary factors such as type of carbohydrate in the diet, level of feed intake, level of production (e.g. annual milk production in dairy), digesta passage rate, presence of ionophores, degree of saturation of lipids in the diet, environmental factors such as temperature, and genetic factors such as efficiency of feed conversion (Kebreab et al., 2006a).

3.2 Modelling Methanogenesis

Crucial to the evaluation of the many potential emission reduction strategies is an understanding of the underlying biological mechanisms. The most appropriate mitigation strategy for any given scenario depends on the farming system, itself the result of many complex interrelationships. This complexity and the desire to achieve significant reductions in emissions have led to several attempts to model methanogenesis from ruminant livestock. Mathematical models offer the potential to evaluate intervention strategies for any given situation, thereby providing a low cost and quick estimate of best practice. Models of methanogenesis can be classified within two main groups. Firstly, there are the statistical models that relate directly the nutrient intake with methane output, which includes emission factors provided by IPCC (2000). Secondly, there are the dynamic mechanistic models that attempt to simulate methane emissions based on a mathematical description of ruminal fermentation biochemistry.

3.2.1 Statistical models

Statistical modelling has been used as a tool to describe empirical relationships between the animal and enteric methane production over many years (e.g. Blaxter and Clapperton (1965)). The statistical models tend to be well suited to practical application for rapid diet evaluation or larger scale inventory purposes. The IPCC publishes methodology for the construction of large scale inventories and describes a three step process to estimating emissions for the purpose of regional or national inventories. Initially, the population is divided into subgroups corresponding to those classes of livestock for which separate emission factors can be estimated in the second step of the process. Separate emission factors are derived for enteric fermentation and manure storage. The final stage involves multiplying the emission factors by the subgroup populations and then combining to deliver an estimate of total emissions. On the face of it this is a very straightforward process worthy of no further description. However, it should be noted that whilst the official IPCC guidelines involve utilization of their recommended methodology to produce the individual emission factors using either a simplified (Tier 1) or more detailed (Tier 2) approach, it would be possible to substitute other models to arrive at the required factors. Having said this, care should be taken to avoid introducing unnecessary complexity into a system that is by its very nature full of broad assumptions about animal numbers and type.

Extant statistical models that estimate methane emissions have been given by Kebreab et al. (2006a). Similar to the emission factors, the statistical models will provide a useful input into inventory calculations for broader scale modelling of emissions from groups of animals or regions, however, one should be aware of their inadequacies. The limitation of these statistical models lies with their tendency to be unreliable predictors of emissions when applied outside of the production systems upon which they were developed. Factors including, species, physiological age or condition, nutrition and management all contribute to variable emissions, thereby tying statistical models to the factors and range of data that were used in their construction.

3.2.2 Process-based Models

Unlike their statistical counterparts, dynamic models include time as a variable and they tend to be more mechanistic in their construction. This type of model has been applied successfully on several occasions to predict methane emissions from ruminants (Mills et al., 2003). However, they too are not without their limitations and they may not deliver quick solutions based on very limited dietary information. By definition mechanistic models describe in more detail the fermentation processes occurring in the gut that result ultimately in the formation of methane as a sink for excess hydrogen. Baldwin et al. (1987) described a scheme for calculating the sources and sinks of this reducing power during fermentation. Ulyatt et al. (1991) evaluated this model using independent data for New Zealand livestock and compared predictions with those from the models of Blaxter and Clapperton (1965) and Moe and Tyrrell (1979). Ulyatt et al. (1991) highlighted the improved prediction seen when using the mechanistic model although they note that the predictions were not without bias. The same scheme was incorporated subsequently into the whole rumen model of Dijkstra et al. (1992), firstly by Benchaar et al. (1998) and then with revisions by Mills et al. (2001) and used to evaluate the potential impact of various mitigation options. Indeed, this model has been applied to suggest the most effective nutritional strategies for limiting emissions whilst maintaining an adequate nutrient supply to the host animal (Mills et al., 2003), and also in the broader context of limiting emissions of both methane and nitrogen pollutants from dairy production (Kebreab et al., 2006b). The model requires detailed information on diet such as dry matter intake, types of carbohydrates and their degradabilities, protein concentration and degradability, and amount of lipid in the diet.

3.3 Future developments in modelling and data requirements

There have been numerous studies conducted in the last 40 years which have the potential to be used as a source for development/refinement of models to accurately predict methane emissions from enteric fermentation. As described above, methanogenesis is affected by various factors and those studies report a select set of conditions, which limit their usability in integrating the studies. At the minimum, every study needs to report feed intake (amount and description) and methane output. Even at this basic level, a significant barrier to applying any model that attempts to relate available nutrition to methane emissions has been the poor description of intake. It has been shown that as the rate of fermentation increases due to the feeding of increased readily fermentable carbohydrate, the rate of methane emission declines per unit of feed degraded (Pelchen and Peters, 1998). This fits neatly with observations of reduced methanogenic activity as rumen pH declines. Therefore, intake data should include amount and types of carbohydrate consumed. The data would be useful if the feed components (in kg/d), such as starch, NDF, simple sugars, protein and lipids with associated degradabilities of carbohydrates and protein were given. A longer term view is also important when considering how to account for changes in methane emissions with the inevitable progression from one physiological state to another. As time advances, animals grow and develop and they move from juvenile to adulthood. Subsequently they will also experience physiological changes as they progress through pregnancy and lactation. Therefore, physiological state of the animal (e.g. non-lactating, if lactating then days in milk, parity, etc.) would give strength to the data. Animal weight should be reported in case there is a need for scaling by some of the models. Unlike other models that predict nutrient balances (therefore require measurement of various outputs), methane models are input driven, therefore, the better the quality of input in terms of dietary description, the more freedom in selecting or developing a model. With advances in measurement techniques, it is assumed that methane output is accurately measured in a controlled environment.

Several studies have observed that there can be significant variation in emissions between apparently similar individual ruminants subjected to the same experimental treatments. Such effects are most apparent when expressed as methane yield as a percentage of gross energy intake. Blaxter and Clapperton (1965) were first to demonstrate this phenomenon in sheep and cattle housed in open circuit calorimeters. Subsequent work by Pinares-Patino et al. (2003) has indicated that this is a real long-term effect, even in more natural grazing conditions, although the results of an earlier study were less conclusive (Pinares-Patino, 2000). Unfortunately for those wishing to model this variance, the underlying causes are not clear. It could be that nutritional factors such as differences in diet selection are partly responsible, in which case the challenge to the modeller is limited to defining differences in nutrient intake.

4 Greenhouse Gas Emissions From Manure Storage

Globally, approximately 0.2-2.5 Tg N_2O-N and 34 Tg CH_4 is produced annually from manure storage (Berges and Crutzen, 1996). Manure is stored in liquid or solid form, or alternatively in cases where animals are left in pasture, no storage is used. Feces and urine excreted by animals, plus bedding and/or water used in barns are flushed or removed into storage until field application is carried out. The Intergovernmental Panel on Climate Change (IPCC) (2000) provides a description of the main types of storage systems, as popular use of these systems varies worldwide. Typically, storage systems are grouped according to the total solids (TS) content of the manure, with solid, semi-solid and liquid systems referring to >20, 10-20, and <10% TS, respectively. Liquid manure systems are considered important sources of CH_4, whereas solid storage is estimated to

Table 1: Greenhouse gases associated with animal production, microbial processes responsible for their production and/or consumption, and factors controlling processes.

Gas	Production/ Consumption Process	Substrate	Controlling Factors
Methane (CH_4)	Methanogenesis/ Methanotrophy	H_2,CO_2, Organic acids	O_2(-)*,temperature, pH
Nitrous Oxide (N_2O)	Nitrification	NH_4^+	O_2(+)***
	Denitrification	NO_3^-	O_2(-)**, organic C

* also consumption process
** indicates lack of O_2 favours process
*** indicates presence of O_2 favours process

be a significant source of both CH_4 and N_2O (Janzen et al., 1998).

Availability of organic matter and anaerobic conditions in manures favour the production of CH_4 by methanogens, with some consumption of CH_4 occurring in the portion of the manure with high O_2 content such as in crusts (Petersen et al., 2005)(Table 1). Presence of ammonium and some O_2 in solid or aerated liquid manures may lead to N_2O production through nitrification; however this process usually results in relatively low N_2O emissions. Denitrification is considered the main microbial processes resulting in N_2O emissions from manure, and this process is dependent on nitrate production through nitrification, and requires low O_2 availability (Table 1). Ultimately, modelling of greenhouse gas emissions from stored manure requires an in-depth understanding of the microbial processes producing and consuming these gases, as well as their controlling factors. Truly mechanistic, dynamic, process-based models attempt to describe these processes at the cellular level, with state variables (eg. nitrate concentration) changing according to rate of microbial consumption/production (eg. denitrification/nitrification) as affected by controlling factors (eg. O_2). Empirically based models use macroscale variables (eg. water content) as surrogates, and often combine several fundamental concepts into one factor that is applicable for a certain set of conditions. The 'emission factor' approach is an example of the latter, and is discussed in detail in the following section. A discussion on process-based models follows.

4.1 Emission Factor Approach

Modelling GHG emissions from manure storage has been largely carried out using the emission factor (EF) approach, as detailed by IPCC methodology (IPCC, 2000). In this approach (Tier 1, IPCC (2000)), emissions of CH_4 are obtained by multiplying the population of animals in each livestock category by an EF (kg CH_4 head^{-1} yr^{-1}) specific for the given category, and country or region. The approach for N_2O is similar with EF expressed in kg N_2O-N (kg N)$^{-1}$ excreted. For CH_4, a refinement of this approach has been proposed, where EF is a function of maximum methane production potential for a given manure type, volatile solid (VS) content of manure, as estimated from animal diet (dry matter intake, energy digestibility and ash content), and a methane conversion factor that takes climate and type of manure storage into account (Tier 2, IPCC (2000)).

The EF approach is well suited for national GHG inventories, as it requires activity data that can be obtained relatively easily, such as number of animals. The disadvantage of this approach is that mitigation practices often cannot be evaluated, as many important processes for GHG emission are not captured in the EF equations. For example, in the case of Tier 2 EF (IPCC, 2000), changes in animal diet other than VS content would not affect predicted CH_4 emissions, while there is experimental evidence that low protein diets can result in lower CH_4 emissions (Velthof et al., 2005). Further refinement of the EF approach to capture animal and manure management practices would require an extensive dataset of emission measurements. It is important to ensure that current and future efforts in GHG flux measurements collect supporting data that would allow for derivation of emission factors as a function of various animal and manure management indicators.

In a recent study, Park et al. (2006) measured half-hourly CH_4 fluxes from liquid swine manure stored in concrete tanks, which were averaged to obtain monthly flux means, and then converted to a monthly emission per animal, using the storage tanks' surface area and the number of animals at each farm. Data obtained for the three measurement sites were then pooled, and an annual CH_4 emission factor (EF) was obtained by summing monthly emissions, and interpolating for two months with missing data (September and December). Similarly, DeSutter and Ham (2005) obtained an EF for anaerobic lagoons through measurement of biogas fluxes over 1-year. In both studies, comparison with IPCC EF was possible since CH_4 fluxes were measured over the course of a year. Interestingly, the IPCC-derived EF overestimated measured EF in both studies. DeSutter and Ham (2005) speculated that CH_4 losses from barn storage pits could potentially account for the observed difference, as IPCC EF attempt to quantify CH_4 emissions from all manure generated per animal over one year. In the IPCC EF this effect is quantified through the VS production per animal per year, which provides the substrate for CH_4 production. Not all VS produced ends up in the outdoor storage, potentially explaining the observed discrepancy between measured and derived EF.

An independent measurement of fraction of excreted VS that reaches anaerobic lagoon storage would allow for a direct comparison of measured and IPCC-derived EF. This is also applicable to Park et al. (2006)'s study, which aimed at comparing United States Environmental Protection Agency(USEPA) and IPCC derived methane conversion factor (MCF) with a measured MCF. While the measured MCF compared favourably with USEPA derived values based on manure temperature (0.22-0.25), measurements of excreted VS and VS in manure would have allowed for further testing of the IPCC Tier 2 EF approach. Due to the inverse relationship between VS and MCF derived from EF, an uncertainty of $\pm 30\%$ in average estimated VS in manure would have resulted in changes in estimated MCF between 42 to -23%.

4.2 Process-based Models

Few models describing process that lead to GHG emissions from stored manure under ambient conditions exist currently. Recently, Sommer et al. (2004) proposed algorithms for a model that quantifies CH_4 emissions from liquid manure during storage, and N_2O emissions from soils after field application of slurry (Table 2). Methane emission during storage is modelled as a function of degradable and non-degradable VS, and indoor or outdoor air temperature (assumed equal to slurry temperature). Volatile solid accumulation between storage emptying is considered, although it is not clear if VS consumed during methanogenesis is subtracted from VS in storage. Nitrous oxide emission from soils are modelled as a function of VS, slurry N and soil water potential, and using emissions factors for denitrification and nitrification that occurs in 'clumps' of added slurry, and for nitrification that occurs in soils. Although this approach has the merit of linking CH_4 and N_2O fluxes through the carbon and nitrogen cycle, some of the empirical equations used are probably only valid for the specific slurries studied by Sommer et al. (2004). Also, these authors cite a lack of GHG emission data for manure storage available for testing of their model.

Due to the controlled nature of the anaerobic digestion process, there are several models that describe methane production based on the kinetics of fundamental processes (hydrolysis, acetogenesis, metahogenesis) and the hydrodynamics of digesters (Keshtkar et al. (2003); Escudié et al. (2005); and cited references therein). These models could form the basis for development of a process-based model of GHG emissions from stored manure, but clearly such a model would need to include the complexity of O_2 diffusion into the manure pile (for solid systems) or liquid surface layer, CH_4 diffusion and ebullition to manure surface, manure temperature variations according to weather conditions, and other factors.

Models describing processes that lead to N_2O emissions from soils have been developed (Li et al., 1992), and in principle these algorithms could be applied to emissions from solid manure storage. However, the spatial variability of air temperature, substrate concentration and airflow through manure piles (Wolter et al., 2004) add additional complexities to the modelling effort.

4.3 Integrated Models

Ideally, models dealing with the GHG from manure management should be integrated with models that describe processes that extend beyond the storage tank, that is, through the AMSC continuum. Understandably, such efforts do not use process-based approaches for the modelling of GHG emissions from each 'pool', but rather an emission factor approach, and focus on the flows of nutrients between different pools.

Schils et al. (2005) suggest a framework for full GHG accounting, where both direct and indirect emissions (eg. from tractor usage) are estimated from the entire farm system, rather than from one component alone. The model divides a farm into five sub-models, or pools, of which manure storage is one. Inputs to the manure pool are in part derived from outputs of the animal and enteric fermentation pool, and similarly, outputs from the manure pool are inputs for modelling emissions from manure-applied soils. IPCC emission factors are used in the model when data are not available. Specific inputs required to estimate CH_4 and N_2O using the Schils et al. (2005) model are listed in Table 2.

Phetteplace et al. (2001) used IPCC emission factors and equations in a farm-scale model of N_2O and CH_4. The model included factors such as milk or meat production, diet characteristics, and manure management, which are more accurate when taken on a farm by farm basis, rather than from a national average. Another farm-scale study used more recent figures for manure storage and N-excretion rates to prepare an improved IPCC model, which resulted in significantly higher estimates (Brown et al., 2001).

Recently, a committee of researchers examining air emissions from animal feeding operations found a whole farm approach for dealing with gaseous losses was needed (NRC,

Table 2: Comparision of model units required for emission factor and process-based models of greenhouse gas emissions from animals and manure storage

Type of Model	Parameter modelled	Units	Inputs	Source
Empirical	CH_4 from animals	kg CH_4/head/yr	-number of animals -type of animals(species,lactating) -emission factor (EF) for each type of animal	IPCC (2000)
	CH_4 from animals	MJ CH_4/day	-metabolizable energy intake -starch and acid detergent fibre intake	Mills et al. (2003)
	CH_4 from manure	kg CH_4/head/yr	-number of animals using manure storage -type of manure storage -volatile solids excreted per animal(VS) -methane conversion factor(MCF) -ultimate methane yield(B_o)	IPCC (2000)
	N_2O from manure	$kgN_2O\text{-}N(kg\ N_{excreted})^{-1}$	-type of manure storage -N content of manure -number of animals using storage	IPCC (2000)
	CH_4 from animals and manure	kg CH_4/head/yr	-animal production stage/class -animal age and body weight -amount of meat/milk produced -feed type -feed intake -manure management	Phetteplace et al. (2001)
Process-based	CH_4 from animals	kg CH_4/day MJ CH_4/day moles CH_4/day	-dry matter intake -volatile fatty acids (and lactic acid) in diet -NDF, degradable NDF, total starch, degradable starch, soluble sugars -N content, ammonia N in diet, indigestible protein rate of degradation of starch and protein	Kebreab et al. (2004)
	CH_4 from manure	g CH_4/day	-proportion of degradable and non-degradable VS in manure -daily VS loading rate in-house and outside store -emptying frequency -potential and actual methane yield -manure in-house residence time -housing air temperature -monthly mean air temperature (assumed equal to slurry temperature)	Sommer et al. (2004)

2003). Mitigation of GHG from farming operations is important, but should be viewed within the context of other pollution issues. It is important to be aware of the impact that mitigation measures may have on other pollution problems. Altering one aspect of a nutrient cycle can drastically affect other components within that cycle. For instance, management practices which result in reducing N_2O loss, yet cause an increase in NH_3 volatilisation or mineral-N leaching to groundwater, should not be used for GHG mitigation, as the problem has just been altered to another form.

4.4 Standards for Reporting of Greenhouse Gas Fluxes

As discussed in Kebreab et al. (2006a), methods for quantification of gaseous fluxes from stored manure are based on methods developed for measurement of gaseous emissions from soils, and can be classified into chamber or micrometeorological methods. These methods yield a flux (in strict terms a flux density), i.e. mass of gas per area per time, averaged over the measurement period (typically >30 min). When chamber methods are deployed in a laboratory setting a known volume or mass of manure is used, so that often fluxes are reported in units of mass of gas per volume (or mass) of manure per time (Massé et al., 2003). In the case of anaerobic digesters, treatment design takes into account volatile solid loading rates, and methane production is often expressed as volume or mass of gas per mass of added volatile solid per time (Umetsu et al., 2005). Gas emissions from solid manure piles have been expressed on a manure dry matter basis, which requires careful monitoring of manure dry matter content, as decomposition significantly decreases this value over time (Pattey et al., 2005; Wolter et al., 2004). As detailed above, EF consists of expressing flux as mass of gas per head per year for a given animal category. In order to account for differences in animal size, some authors have expressed fluxes as mass of gas per kg of live animal weight per time (Laguë et al., 2005). There is evidently a multitude of ways in which gas flux can be expressed, clearly making the task of comparing results from different studies very difficult (Table 3). Agreement on a reporting standard may be difficult due to the diverse disciplines involved in the study of processes and gas emissions from manure. However, we suggest that fluxes be reported 'as measured', which for most field experiments consists of a flux density, and that detailed measurement on the emitting substrate be reported simultaneously. For CH_4, which is produced from decomposition of volatile solids, a measure of total amount of VS (degradable and non-degradable) in the manure tank, including daily/weekly loading rates, is recommended. For N_2O, total nitrogen in the manure, including the partitioning into organic and mineral (NH_4^+, NO_3^-) forms, needs to be quantified.

This raises issues related to manure sampling procedures, due to the non-homogeneous nature of manure, particularly the stratification that occurs in liquid manures (Ndegwa and Zhu, 2003). In solid manure piles, stratification of mineral N forms can also occur, with NO_3^- usually only present in the drier surface layer, where nitrification apparently can take place (Brown et al., 2001; DeSutter and Ham, 2005). Advances in infra-red spectroscopy for real-time analysis of dry matter and organic matter in liquid manure samples may provide the option for frequent measurement of manure composition (Saeys et al., 2005).

Finally, the detailed characterization of emitting substrate (i.e. manure composition over time) needs to be accompanied by a description of the animals generating the manure, and the manure management used at the facility.

Table 3: Results from studies in the literature examining CH_4 and N_2O emissions from animal and manure storage

Source	Animal/ Manure	Recorded Value	Unit	Measurement Method/Period
Belyea et al. (1985)	Dairy	8.9	MJ d^{-1}	Respiration mask
Boadi and Wittenberg (2002)	Dairy	9.5	MJ d$-$1	Tracer gas (SF_6)
	Beef	9.5	MJ d$-$1	Tracer gas (SF_6)
Boadi et al. (2002)	Steers	11.4	MJ d$-$1	Tracer gas (SF_6)
Johnson et al. (2002)	Dairy	21.4	MJ d$-$1	Tracer gas (SF_6)
Kinsman et al. (1995)	Dairy	20.3	MJ d$-$1	Infrared gas analyser from barn
McCaughey et al. (1999)	Beef	13.7	MJ d$-$1	Tracer gas (SF_6)
McCaughey et al. (1997)	Steers	8.9-11.3	MJ d$-$1	Tracer gas (SF_6)
Sauer et al. (1998)	Dairy	20.7	MJ d$-$1	Infrared gas analyser from barn
McGinn et al. (2004)	Beef	9.1	MJ d$-$1	Chamber
Husted (1994)	Swine	0.4-35.8	g CH_4 m^{-3} d^{-1}	Periodically from Oct.1, 1991 to Sept.31, 1992
	Dairy	0.0-34.5	g CH_4 m^{-3} d^{-1}	
Khan et al. (1997)	Dairy	2-100	kg CH_4 ha$-$1 d^{-1}	Four days in May and 2 days in Aug., 1995
Kaharabata et al. (1998)	Swine	74	kg CH_4 m^{-2} yr^{-1}	Jun. 12 to Nov. 20, 1995
	Dairy	56.5	kg CH_4 m^{-2} yr^{-1}	
Sharpe and Harper (1999)	Swine	52.3	kg CH_4 ha^{-1} d^{-1}	Periodically over the entire year of 1996
Harper et al. (2000)	Swine	0-3.6	kg N_2O ha^{-1} d^{-1}	Summer 1994 to Summer 1996
Sommer et al. (2000)	Dairy	<0.01-1.4	g CH_4 m^{-3} hr^{-1}	Fall 1996, Summer 1997
Sharpe and Harper (2002)	Swine	5.3-115.3	kg CH_4 ha^{-1} d^{-1}	Periodically from May 1997 to Feb. 1998
Massé et al. (2003)	Dairy	1.46-2.17*	L CH_4 m^{-3} d^{-1}	Laboratory, 180 day or 272 day storage periods, total solids (5%, 10%), and temperature (10°C, 15°C) varied
		1.06-14.83**	L CH_4 m^{-3} d^{-1}	
	Swine	5.36-30.00*	L CH_4 m^{-3} d^{-1}	
		4.97-28.08**	L CH_4 m^{-3} d^{-1}	
Külling et al. (2003)	Dairy	13.6-16.1	μg CH_4 m^{-2} s^{-1}	Laboratory, 5-7 weeks storage, comparing diets
		0.20-0.40	μg N_2O-N m^{-2} s^{-1}	
Park et al. (2006)	Swine			
Wolter et al. (2004)				
Pattey et al. (2005)				
Laguë et al. (2005)				

*Short storage

**Long storage

In summary, for GHG emissions from manure storage, studies that seek to measure gas fluxes or treatment impacts for mitigation are encouraged to include the following measurements:

1. *Emission rate expressed as mass CH_4 or N_2O per area and per time (e.g. mg m^{-2} s^{-1}).*

2. *Dimensions of manure storage.* Dimensions are required in order to calculate volume and surface area of the emitting storage unit. The change in level of liquid manure in tank over time or the loading rate is also useful in order to associate emissions with a manure volume. For solid manure piles, monitoring of the volume and bulk density are required.

3. *Composition of manure (TS, VS, TN, mineral N).* This information combined with manure volume would give a measure of substrate amount for total GHG emissions.

4. *Length of manure storage time.* Methane production has been shown to be related to the length of storage time for liquid dairy manure, but not for liquid swine manure (Massé et al., 2003). Moreover, measured mean gas fluxes need to be integrated over the storage period in order to calculate annual emissions. Frequency of agitation or emptying of manure storages should be recorded and included in reporting.

5. *Animals using storage system.* IPCC emission factors are on a per head basis, thus comparison with these factors requires inclusion of the number of animals contributing to the emissions. Uniformity in reporting is desirable as some studies report on the basis of animal units, by animal weight (eg. kg CH_4/1000 kg body weight), or by product weight (eg. kg CH_4/kg milk). Ideally, reporting should include number of animals per standard weight category, and productivity level (weight gain, milk production, etc.), as well as animal diet and feed intake characterization.

4.5 Supporting Measurements Required for Modelling of Greenhouse Gas Emissions from Animal Manure

The development of models to predict GHG emissions from manure storage requires the measurement and reporting of additional variables that are often missing in published studies. As discussed above, manure composition and characteristics such as pH, temperature and O_2 concentration are very important for the understanding of processes leading to GHG production, and these variables should be quantified over the course of experiments designed to measure GHG fluxes (Table 4). The manure management practices of the studied farm should be described so that the measured gas fluxes can be interpreted accordingly. In particular, dynamic variables such as loading rate would allow for a link between manure tank and animals generating the manure. For outdoor storage, the environmental conditions which will determine manure temperature are important, as these would be inputs for models aiming at describing gas fluxes from manure. These data are often available from local weather stations, but if unavailable from these sources, variable should be monitored by researchers during the study period. Finally, a complete description of the animal production operation, with emphasis on the barn units using the monitored storage tank is fundamental (Table 4). This would ensure that in the future modelling of manure processes can be linked to animal nutrition modelling efforts.

Table 4: Factors affecting production and emission of greenhouse gas from animals and manure storage

Animal Characteristics	Manure Characteristics	Management Practices	Environmental Conditions
Number	Total Solids	Forage/silage quality	Air temperature
Species	Volatile Solids	Feed intake restriction	Wind speed
Age	pH	Use of Ionophores	Rainfall events
Size/Weight	Volatile Fatty Acids	Genetic selection	Solar radiation
Feed intake	Sulphur	Residence time	Air humidity
Diet composition*	Phosphorus	Type of storage	
Alternate H_2 sinks	NO_3^-, NH_4^-	Storage dimensions	
Form of N excretion	Degradable C	Existence of crust	
Physiological state	Oxygen	Use of manure cover	
Rumen pH	Temperture	Treatment technology	
Rumen microbes		Timing and rate of agitation and loading	

*type of carbohydrate,VFA stoichiometry,forage:concentrate ratio,degradability,amount of lipids

5 Conclusion

Modelling has been used to summarize and give an added value to research conducted in relation to greenhouse gases. Although there are a number of models developed thus far, further advances in modelling methane emissions will probably result from a strengthening of the mechanistic description of the underlying fermentation biology in the gastrointestinal tract of farm livestock. At the animal level, statistical approaches will continue to be relevant where a specific solution is required and data to parameterize more complex mechanistic models is unavailable. Future work should report a detailed description of the diet such as the type of energy, protein and their degradabilities, amount of lipid and animal descriptors such as weight, age and physiological state.

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