N_2O EMISSIONS FROM ANIMAL WASTE MANAGEMENT SYSTEMS

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ABSTRACT

Livestock and poultry excrements (dung and urine) contain nitrogen that is substrate for microbial nitrification and denitrification processes. A gaseous nitrogen species that is released from these processes into the atmosphere is nitrous oxide (N_2O). This paper provides some background information for the proper estimation of N_2O emissions from animal waste (produced by livestock and poultry) during storage and treatment of the animal waste. The noun "animal waste" encompasses all animal excrements, including possible bedding material, water and micro-organisms.

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)* provide a transparent framework to calculate national emissions from animal waste during storage and treatment. Seven types of Animal Waste Management Systems (AWMS's) are distinguished. In the *IPCC Guidelines*, emissions of N_2O from AWMS's are assumed to be linearly related to the amount of N in the animal waste. This relationship is expressed as $N_2O\ emission_{(i)} = A_{(i)} \bullet EF_{(i)}$, where $A_{(i)}$ is the total amount of nitrogen (N) in the AWMS of type *(i)*, and $EF_{(i)}$ is the emission factor for the AWMS of type *(i)*.

Good practice in inventory preparation involves a series of six consecutive steps:

- Characterization of livestock and poultry population;
- Determination of the mean annual N excretion for each animal category;
- Determination of the amount of animal waste N in the various AWMS's;
- Correction of the amount of N in the AWMS's for possible N losses via ammonia volatilization;
- Application of the proper emission factor to each AWMS, and
- Calculation of N_2O emissions from: $N_2O_{(AWMS)} = \sum_{(T)} [N_{(T)} \bullet Nex_{(T)} \bullet AWMS_{(T)} \bullet EF_{3(AWMS)}]$

Good practice in inventory preparation requires that proper activity data and emission factors are used, and that the proper procedures for "upscaling" and "quality assurance and quality control" (QA/QC) are applied. Application of *good practice* in inventory preparation will improve the transparency and completeness of the inventory and ultimately the accuracy and quality of the estimated total emissions.

So far, the uncertainties in the N_2O emission estimates from AWMS's are large. This is mainly due to the uncertainties in the emission factors and to the uncertainties related to the actual management of the animal waste in the various AWMS's. A number of possible categories of biases and errors, as sources of uncertainties in inventory preparation, have been identified.

In this paper we make a number of suggestions to further improve the *IPCC Guidelines.* These suggestions relate to a refinement of the categories "Other animals" and "Other systems", and to the application of a correction factor for N losses during storage and treatment of the animal waste in the AWMS's. Suggestions were also made to improve the quality of the inventories of livestock, poultry and AWMS's. There is a considerable lack of proper criteria and information about AWMS's in practice. Finally, we make a plea for a coordinated research action to improve the quality of the emission factors. The uncertainties in the emission factors contribute most to the uncertainty in the overall N_2O emission. Whenever possible, emission factors should be related to: (i) the aeration states of the animal waste in the AWMS's, (ii) temperature and (iii) the duration of the storage process, as these are the major controlling factors.

1 INTRODUCTION

On a global scale, Animal Waste Management Systems (AWMS's) are important sources of nitrous oxide (N_2O). It has been estimated that AWMS contribute about a third of the total N_2O emission from agriculture, which amounts to about 6 Tg N_2O-N per year (Mosier et al., 1998). Hence, AWMS's contribute as much as about 14 percent to the estimated total global emissions of about 14 Tg N_2O-N into the atmosphere. The term "animal waste" is used here as a generic noun for all types of animal excrements (dung, urine, waste), including possible additives (bedding material, straw, water, micro-organisms, etc.). The term "animal waste management system" is used here as a generic noun for all types of storage and treatment of animal waste, except the application of the animal waste on the land.

The N_2O from AWMS's originates predominantly from the microbial processes of nitrification and denitrification (Oenema et al., 2001). Nitrification is the microbial transformation of ammoniacal nitrogen (NH_4^+-N) into nitrate nitrogen (NO_3^{--}-N. Denitrification is the transformation of NO_3^- into nitrogen gas (N_2). Nitrous oxide is released from the nitrification process as a by-product, the amount of which depends on the rate of the nitrification process, oxygen concentration, pH, temperature, and the microbial community. In the denitrification process, N_2O is an intermediate product, which may escape when the rate of N_2O production and the rate of N_2O consumption are not well synchronized and synlocalized. The amount of N_2O released from the denitrification process is a function of the amounts of NO_3^- and metabolizable organic carbon, the oxygen concentration, pH, temperature, and the microbial community.

Qualitatively, the controlling factors of nitrous oxide production and emission at the process level are rather well understood. This holds as well for nitrous oxide from animal waste at the process level. However, our quantitative understanding of N_2O emissions from the various sources is still far from complete. This holds as well for N_2O emissions from AWMS's. There is a wide range of N_2O emissions in types of animal waste management systems in practice. The waste and the conditions of the management system may vary from site to site and also from time to time. In fact, we know surprisingly little about what farmers actually do and how they manage the storage and utilization of waste, and how this translates into emissions of N_2O into the atmosphere. As a result, the uncertainty in the estimated N_2O emission is large (Mosier et al., 1998). The uncertainty is related in part to the stochastic nature of the emitting processes in AWMS's, and in part also to the poor availability and quality of data and to the methodology applied for calculating areal estimates (e.g. Van Aardenne, 2002).

The *IPCC Guidelines* (IPCC/OECD/IEA, 1997) provide a step-by-step guide to countries in the preparation and submission of annual greenhouse gas emission inventories, including N_2O from AWMS's. The *IPCC Guidelines* provide standard tables, worksheets, units, default values for activity data and emission factors, and time intervals for reporting the emissions. Countries are invited to use their own estimates for activity data and emission factors, when these values are considered more accurate than the default values provided by the *IPCC Guidelines*. These values should be sustained by proper documentation. It is generally agreed that the use of *good practice* procedures in the selection of activity data and emission factors can reduce uncertainties in emission inventories. Application of *good practice* in inventory preparation will provide the most accurate estimates of actual emissions. It will also facilitate the process or review to qualify uncertainties and to cross-check national estimates with independent calculations. Furthermore, it may provide an appropriate basis for compliance with the commitments under the Kyoto Protocol.

The IPCC Expert Meeting on *Good Practice* in Inventory Preparation: Agricultural Sources of Methane (CH_4) and Nitrous Oxide(N_2O) in Wageningen (February 24-26, 1999) provided a forum of technical experts familiar with greenhouse gas emissions from agriculture, to discuss and agree upon *good practice* guidance for CH_4 and N_2O emissions from agriculture. The present paper has been prepared as a background paper to facilitate the discussion in the sub-group "Nitrous oxide from animal waste management systems" of the IPCC Expert Meeting. The purpose of this background paper is to briefly review the guidelines for *good practice* in national inventory management of N_2O from animal waste management systems, and to suggest improvements of the guidelines, so as to improve the accuracy of national estimates of N_2O emissions from animal waste management systems. It addresses key issues related to inventory preparation, i.e., (i) methodological issues, (ii) completeness of the inventory, (iii) assessment of inventory quality, and (iv) assessment of uncertainties.

2 CURRENT STATE OF INVENTORY METHODOLOGIES

Basically, there are various options to quantify N_2O emissions from AWMS's, ranging from frequent direct measurements to approximations, using activity data and emissions factors. Evidently, direct measurements provide the most accurate estimates of the N_2O emissions from AWMS's, but direct measurements are not an appropriate option for getting a total average emission per country. Nitrous oxide from AWMS's is the sum of numerous small and diffusely spread sources all over the world, and these cannot all be measured at the desired level of accuracy and precision. Furthermore, process-based models are still in the phase of development and testing (validation), and are not yet a suitable alternative either. Hence, approximations such as those in the IPCC Guidelines provide the best alternative at this moment.

The *IPCC Guidelines* provide a transparent framework to calculate national emissions from AWMS's (IPCC/OECD/IEA, 1997). Seven categories of Animal Waste Management Systems (AWMS's) are distinguished in section 4.2 'Domestic Livestock' of Chapter 4 'Agriculture' of the *IPCC Guidelines*, namely

- anaerobic lagoons;
- liquid systems;
- daily spread;
- solid storage and drylot;
- pasture range and paddock (grazing);
- used as fuel, and
- other systems.

However, for reasons of convenience, the category "used as fuel" is reported henceforth under section 1.3 of Chapter 1 Energy. Furthermore, for the categories 'daily spread' and 'pasture range and paddock', there is essentially no intermediate storage and treatment of the animal waste, because the dung and urine are directly transferred to soil. Hence, the categories 'daily spread' and 'pasture range and paddock (grazing)' are reported under section 4.6. Agricultural soils of Chapter 4 of the *IPCC Guidelines* (IPCC/OECD/IEA, 1997).

The *IPCC Guidelines* assume that a certain fraction of N contained in animal waste in the AWMS's is released as N_2O into the atmosphere, during storage and treatment of the animal waste. The fraction of N_2O emitted, i.e. the emission factor, is assumed to be linearly related to the amount of N in the animal waste, but it varies for the various types of AWMS's. This can be represented as:

$$\boxed{N_2O_{\text{ emission(i)}} = A_{(i)} \bullet EF_{(i)}}$$

Where:

$A_{(i)}$: the total amount of nitrogen in the AWMS of type (i),

$EF_{(i)}$: the emission factor for the AWMS of type (i).

Emission factors are expressed as the mass fraction of the N in the waste that escapes as N_2O to the atmosphere. It ranges from 0.00 (zero) for daily spread, to 0.001 for anaerobic lagoons and liquid systems, and to 0.02 for dung and urine from grazing animals and for solid storage of waste and drylots. Different emission factors for different AWMS's reflect the differences in conditions during storage and treatment of the waste, and in controlling factors of N_2O emissions (i.e. oxygen content, nitrate content, pH, temperature, etc.).

The amounts of N in the AWMS are estimated from the amounts of N excreted by the various types of animals. Default values of N excretion have been presented by the *IPCC Guidelines* for 6 categories of animals and for the 8 major regions in the world. The amount of N excreted by non-dairy cattle, dairy cattle, poultry, sheep, swine and other animals are corrected for N losses by ammonia volatilization (Mosier et al., 1998).

Urine and dung droppings of grazing animals are suggested to be a dominant source of N_2O (Mosier et al., 1998; Oenema et al., 1997). Approximately 80% of the estimated total N_2O emission from animal excrements originates from grazing animals (IPCC/OECD/IEA, 1997). Most of the non-dairy cattle, dairy cattle, sheep and the category other animals are kept outside in the field. Hence, a large fraction of the N in animal excrements is deposited on pasture. A number of studies have shown that a relatively large fraction of the N from dung and urine in pastures is emitted as N_2O into the atmosphere. The high emission factor has been related to the very high N concentrations in the urine and dung patches, to interactions between nitrogen and carbon cycling in grazed pastures and to the effects of trampling and compaction of the soil by the grazing animal (Oenema et al., 1997). As noted before, the animal waste from grazing animals directly reaches the soil. Hence, the associated N_2O losses have to be reported under Greenhouse Gas Emissions from Agricultural Soils (Section 4.6)

The *IPCC Guidelines* provide a transparent framework to calculate national emissions from AWMS's as briefly summarized below:

$$N_2O_{(awms)} = \Sigma_{(t)} [N_{(t)} \bullet Nex_{(t)} \bullet AWMS_{(t)} \bullet EF_3(_{awms})]$$

Where:

$N_2O_{(AWMS)}$: N_2O emissions from animal Waste Management Systems in the country (kg N/yr)

$N_{(t)}$: number of animals of type t in the country

$Nex_{(t)}$: N excretion of animals of type t in the country (kg N/animal/yr); (1996 IPCC Guidelines, Table 4-20)

$AWMS_{(t)}$: fraction of $Nex_{(T)}$ that is managed in one of the different distinguished animal waste management systems for animals of type t in the country; (see Table 4-21)

$EF_{3(AWMS)}$: N_2O emission factor for an AWMS (kg N_2O-N/kg of Nex in AWMS); (1996 IPCC Guidelines, Table 4-22)

t: type of animal

The estimated uncertainty in the various N_2O sources can be as high as two orders of magnitude (IPCC/OECD/IEA, 1997). The uncertainty in total emissions from a single source follows mainly from the uncertainty in the emission factor, and also from the uncertainty about the amount of nitrogen in animal waste in a specific animal waste management system. Generally, there is less uncertainty related to the agricultural activity data, i.e. the number and type of animals and amount of N excreted per animal. Yet, deviations of actual N excretion from default values may be as large as 30 percent for the various categories of animals. Furthermore, there may be some confusion about different categories of animals (e.g. other animals, dairy cattle versus non-dairy cattle) and whether baby animals are included or not (e.g. piglets and pig; lambs and sheep).

The IPCC/OECD/IEA Working Group on developing the *IPCC Guidelines* recommended that future inventory methodologies should be based on process-based models because of the many uncertainties related to the application of linear emission factors to estimating N_2O emissions from agricultural sources,. Process-based models should be developed and tested, to check the accuracy of approximations of the *IPCC Guidelines,* and to further improve the estimates in the near future. However, it was also stated that the present knowledge about the complex interactions and about the many controlling factors of N_2O emissions from agricultural sources is incomplete to apply these models right now. Furthermore, there is insufficient experimental data to calibrate and validate these models, at this moment. Hence, the *IPCC Guidelines* provide the best alternative for this moment when proper procedures and guidance are provided.

3 METHOD FOR DETERMINING N_2O EMISSIONS FROM AWMS'S

3.1 Framework of the *IPCC Guidelines* for inventories of N_2O emissions from AWMS's

The method for estimating N_2O from animal waste management systems requires 6 steps:

Step 1: Divide the population of domestic animals into categories. Use the categories provided in the chapter "Domestic livestock" of The *IPCC Guidelines*. To improve the accuracy, we suggest the characterization of each category (average annual population) in terms of age, weight, fodder intake and number of young-ones relative to adults. We also suggest to characterize and specify the animals in the category "other animals". Furthermore, determine the number of animals of each category, and calculate three-year averages, based on monthly-weighted sums.

Step 2: Determine the annual average N excretion rate for each of the distinguished animal categories. Default values are in the *IPCC Guidelines*. We suggest that if there is evidence that the N excretion estimates deviate more than 10 percent from the default values provide in Table 4-20 of the *IPCC Guidelines*, countries are invited to apply their own estimates. These adjusted N excretion rates must be based on published sources, e.g. peer reviewed papers, Organisation for Economic Cooperation and Development (OECD) and the Food and Agriculture Organisation (FAO) reports.

Step 3: Correct the annual average N excretion rate for each category for N losses via ammonia volatilization and denitrification during storage and treatment of animal waste. Currently, there is no correction factor for N losses during storage and treatment in the *IPCC Guidelines.* However, there is ample evidence that significant N losses may occur during storage and treatment of animal wastes, depending on storage conditions and storage duration. Tentatively, a conservative default value of 10% N loss in AWMS's is proposed. Countries should be invited to come up with own estimates, which may be dependent on storage conditions (temperature, aeration, duration). Please note that the amount of N considered in the section "Indirect N_2O emissions" (section 4.6 of the *IPCC Guidelines*) should be corrected for the amount of N that is lost during storage and treatment in AWMS's. Furthermore, note that there is a correction factor for N loss for the animal waste applied to soil.

Step 4: Determine the amount of animal waste N, corrected for N losses via ammonia volatilization and denitrification, in the various animal waste management systems. It is suggested to characterize each AWMS in terms of the operations. Check for consistency in the data; provide N budgets for the animal categories. The sum of the total N intake by the animal via animal feed should equal the sum of the amount of N retained by the animals, the amount of N in animal products, the amount of N volatilized and the amounts of N in the various AWMS. Budgets should be provided on an annual basis.

Step 5: Estimate the N_2O emission factors for each category of animal waste management system. Default values are provided in the *IPCC Guidelines.* However, there is a considerable uncertainty in the default emission factors, up to two orders of magnitude. We suggest that countries use their own emission factors, whenever justified by results of sound experimentation and published in peer reviewed scientific journals. It is likely that climate (temperature) and the amount of N in the waste are important modifiers of emission factors. We believe that coordinated research is needed to lower the uncertainty in the emission factors.

Step 6: Multiply the AWMS's emission factors by the amounts of N in the corresponding AWMS's to estimate AWMS emissions. Sum across the AWMS's to estimate total emissions.

3.2 Recommendation on activity data in the context of good practice

Activity data in the context of this paper refer to numbers and categories of animals as well as to the fractions and types of AWMS's. *Good practice* requires that reporting countries supply information along with numbers that allow an independent authority to check the accuracy and reliability of the data. So far, data on animal numbers seem more accurate than data on type and management of AWMS. For the majority of countries, counting the number of animals has been a long standing tradition. There are proper procedures as well as documents for national (Yearbooks) and international (e.g. to FAO) inventories of livestock and poultry. These procedures/documents, however, do not include AWMS's simply because there has been no commercial incentive to do so.

Evidently, there is an urgent need for accurate information on the management of animal excrements in AWMS's in practice, particularly information about N_2O emission controlling factors. The development of guidelines for a proper inventory and monitoring of AWMS's is therefore necessary. It is also deemed important to convince the policy makers and administrators that the collection of data on this topic must be included in census legislation in order to obtain such data on a regular basis for *good practice* in GHG emissions. An enforcing argument for this is that such data will not only serve to increase confidence incurrent emission estimates but will also be needed to document progress in emissions reduction strategies.

3.3 Recommendations on emission factors in the context of good practice

The *IPCC Guidelines* provide default values for emissions factors for the various AWMS's. They reflect annual mean losses. As such, the default values may differ significantly from the results of some direct measurements. While results from direct measurements reflect one distinct situation, frequently read over short periods, emission factors basically integrate possible effects and variations due to time (one year), climate, management and animal waste compositions.

So far, the default values for the emission factors in the *IPCC Guidelines* are based on a limited amount of experimental data and expert judgement. The uncertainties are large. The AWMS ‘daily spread’ has an emission factor of 0.0 (no range), simply because there is no storage of the animal waste; it is assumed that time period between the moment of excretion and the moment of spreading is too short to emit any N_2O into the atmosphere. However, there are no experimental data to confirm this assumption. A relatively high emission factor of 0.02 has been assigned to the AWMS “Solid storage and drylot”, because of the partial oxic conditions in the animal waste and associated nitrification and denitrification processes, and because of the relatively lengthy storage time. However, there is little experimental data that confirm this estimate (Mosier et al., 1998). A relatively high emission factor of 0.02 has been also assigned to the AWMS “Pasture range and paddock (grazing)”, based on a literature review by Oenema et al. (1997; 2001). Those review indicated that the actual emission factor may range between 0.001 to 0.08. Liquid systems and anaerobic lagoons are suggested to emit little N_2O, because of the anoxic conditions. As a result, there is essentially no nitrification and denitrification going on, except for the surface layer in contact with the atmosphere. An emission factor of 0.001 has been assigned to these systems, but again there is little information that can confirm this estimate. Finally, the AWMS category “other systems” has been arbitrarily assigned an emission factor of 0.005, as this category may include completely anoxic systems as well as systems that contain partly oxic conditions.

A huge effort is needed to increase the accuracy and to decrease the uncertainty. Whenever possible, emission factors should be related to:

- the degree of aeration;
- the storage time, and
- the temperature of the animal waste.

These factors are suggested to be the major controlling factors.

Because of the many factors and interactions involved, there exist the possibility that single measurements within a country for a specific AWMS will not only significantly deviate from the default value, but also from estimates obtained elsewhere. The underlying questions are how to extrapolate these data to other sites and other AWMS’s as well as circumventing the fact that emission estimates vary from year to year simply because new data from measurements show such variation. A coordinated effort is needed worldwide to obtain more reliable emission factors for N_2O from AWMS’s. So far, there are some doubts on the progress of this type of studies. It is clear that this type of studies are more of monitoring than conducting scientific research. Funding agencies may be not so eager to fund monitoring tasks, because little novel information is to be expected from such efforts. Furthermore, the uncertainties that arise from up-scaling remain large. This dilemma requires more attention.

4 COMPLETENESS

Basically, the *IPCC Guidelines* cover all possible sources of N_2O from AWMS’s, hence categories “other animals” and “other systems” are added so as to include animals and systems not specified. When not properly specified, certain categories may be overlooked.

4.1 Other animals

The term “other animals” is a diffuse notation, and risks exist that certain types of animals may be overlooked. The currently specified animal types were selected in order to comply with the categories used in the FAO statistical yearbook. To improve the quality of the agriculture activity data, according to *good practice,* a more detailed animal categories is considered. Animal categories should be detailed enough to provide accurate estimates of numbers and N excretion rates. Moreover, the distinction between agricultural or domestic animals and wildlife animals is not always clear. As a result, emissions from agriculture and from natural or background sources are not separated clearly. Furthermore, it is not always clear whether the number of animals and N excretion include the numbers of young (baby) animals and associated N excretion. Improving the quality of counting the animals in a country will further improve the quality of N excretion rates, and hence, N_2O emission estimates.

There are two listings of animal categories in the *IPCC guidelines*, i.e. one that includes 10 categories of animals, used for the CH_4 emission inventories, and one that includes 6 categories of animals, used in the N_2O emission inventories (Table 1). From a comparison of these two categories, the category “other animals” in the

N_2O emission inventories is found to be an important source of N_2O in some African, Asian and Latin American countries. Furthermore, there are significant differences in N excretions between animals that are now grouped in the category ‘other animals’. For example, amounts of N excretion may vary between goats, horses and buffaloes by a factor of 5. Hence, the use of a more detailed listing for animal categories in Table 1 is recommended. Furthermore, the extension of Table 4.20 on page 4.99 in Volume 3 of the *IPCC Guidelines* should include N excretion rates for goats, camels, horses, mules and asses and buffaloes.

TABLE 1

CATEGORIES OF DOMESTIC ANIMALS INCLUDED IN THE EMISSION INVENTORIES OF N_2O AND CH_4 FROM ANIMALS AND ANIMAL WASTE MANAGEMENT SYSTEMS ACCORDING TO THE IPCC GUIDELINES

CH_4 emission inventories	N_2O emission inventories
Dairy cattle	Dairy cattle
Non-dairy cattle	Non-dairy cattle
Swine	Swine
Sheep	Sheep
Poultry	Poultry
Goats	Other animals
Camels	
Horses	
Mules and Asses	
Buffaloes	

4.2 Other AWMS’s

In The *IPCC Guidelines,* a total of seven animal waste management systems (AWMS’s), including the category “other systems”, have been identified for N_2O emission inventories, whereas, a total of ten categories have been identified for CH_4 emissions inventories (Table 2). The category “other systems” covers all remaining systems in both inventories, thereby assuming completeness. When comparing the N_2O and CH_4 inventories, it follows that the category “other systems” in the N_2O emission inventory includes pit storage, anaerobic digesters and (deep) litter houses mentioned in the CH_4 emissions inventories. The category “other systems” in N_2O emission inventories also encompasses most of the poultry waste storage, i.e. the semi-dry storage of waste from poultry in large poultry stables.

TABLE 2

CATEGORIES OF ANIMAL WASTE MANAGEMENT SYSTEMS (AWMS’S) IDENTIFIED IN THE EMISSION INVENTORIES OF N_2O AND CH_4 FROM ANIMAL WASTE MANAGEMENT SYSTEMS ACCORDING TO THE IPCC GUIDELINES

CH_4 emission inventory	N_2O emission inventory
Pasture range and paddock	Pasture range and paddock
Solid storage	Solid storage and drylots
Drylot	
Daily spread	Dairy spread
Liquid slurry	Liquid slurry
Anaerobic lagoons	Anaerobic lagoons
Pit storage	
Anaerobic digester	Burned for fuel
Burned for fuel	Other systems
Other systems	

The classification of AWMS's for the N_2O inventory in the *IPCC Guidelines* has been adopted from Safley et al. (1992). It must be noted that while animals are to some extent standardized by nature, AWMS's are not. For example, the AWMS "Solid Storage and Drylot" of farm A may differ significantly from that of farm B. Such differences can be larger than the differences in, for example, N-excretion from one dairy cow to another dairy cow. Moreover, census data for the AWMS applied by the farmers are rare. Evidently, efforts are needed from the reporting countries to gather quantitative data on amounts and types of AWMS's. Guidelines for *good practice* should be made for specification of the various AWMS's; how to make the inventories and according to which criteria. Reviews on the national AWMS's can then be used to identify classes, groups and subgroups of AWMS's. With this prerequisite fulfilled, meaningful research could lead to appropriate N_2O emission factors with less uncertainty than those associated with the default ones in the *IPCC Guidelines.*

5 INVENTORY QUALITY

Quality assurance and quality control (QA/QC) is a process that encompasses the whole range of activities and intermediate steps in assuring accurate and high quality data in an inventory (Mangino, 1999). A well-developed and well-implemented quality assurance programme fosters confidence in the final inventory results. The common thread throughout the quality assurance process is the need for thorough documentation and complete transparency (Mangino, 1999). Each group of actors involved in the inventory programme should have the necessary information and full documentation, with which to fulfill its function. Figure 1 outlines the flow of information and the inventory quality process at each step (Mangino, 1999). The first component is internal quality control, which is a system of routine activities to measure and control the quality of the data statistics at farm level, the direct measurements of emissions (factors), and of the inventory as it is being developed. Application of internal quality control systems will minimize biases and errors by specifying procedures to check for consistency, completeness and correctness of the inventory process.

Prerequisite to quality assurance and quality control in the inventory of N_2O emissions from AWMS's are well-documented procedures of data acquisition and data handling. Acquisition of activity data can be done at different scales, frequency and level of detail. The farm-level is the most detailed scale and aggregating the data from all individual farms will yield ultimately the most accurate estimates of activity data. Activity data can be monitored on a monthly basis or on an annual basis. Monthly weighted annual averages yield the most accurate data. In industrialized countries, farms have to report number and type of animals on an annual basis to national agencies that record farm statistics. These primary data are collected at all farms following standard procedures on an annual basis. For other countries, activity data are derived from surveys in representative areas in the field. These are subsequently extrapolated to the whole country. Ultimately, the activity data are compiled in the FAO statistical yearbook, which provides a uniform format for activity data inventories for all countries. Evidently, there are many possible steps involved in the acquisitions of activity data.

In short, quality assurance and quality control require that all actors involved in the emissions inventory share the information. This will ensure that all animal categories and all animal waste management systems are included. The Governmental agencies responsible for emission inventories should carry out the assessments of data quality and completeness. Data published in peer-reviewed international journals should provide the basis for emission factors.

6 UNCERTAINTY ASSESSMENT

6.1 Sources of uncertainty

Uncertainty assessment requires that all possible sources of uncertainty must be evaluated in the complete chain from very beginning of the measurement of primary data (activity data) and the measurement of emissions in the field up to the compilation of work sheets and the establishing of emission estimates per country. Uncertainties arise from biases and errors. *Bias* is defined here as misrepresentation, leading to a systematic deviation of the measurement mean from the true (scientific) mean. *Error* is random variation around the true mean, leading to a confidence interval around the measurement mean. Bias in emission estimates may lead to wrong conclusions, whilst errors complicate the making of conclusions, and in turn may lead to wrong conclusions as well. The term '*accuracy*' is used here as a measure for bias; a high accuracy means that the deviation of the measurement mean from the true mean is small. The term '*precision*' is used here as a measure for error; a high precision means that the variance of repeated measurements (or estimates) is small (Oenema and Heinen, 1999).

Figure 1 Key steps in the inventory QA/QC process

	Farm level	**Research level**
Internal quality control:	Number and categories of animals N budgets calculations	Emission factors N Excretion and N_2O budgets
Documentation:	Farm statistics Internal quality control	Peer reviewed papers Internal quality control
	⇓	⇓
	National Agencies for Farm Statistics	
Review/Quality assurance:	Farm-level inputs of activity data	
Internal quality control:	Compilation of N activity data from farm data statistics	
Documentation:	Results of compilation and results of QA/QC	
Reporting:	Submission of data to Government Agency	
	⇓	
	FAO statistical yearbook	
Review/Quality assurance:	Farm-level inputs of activity data	
Internal quality control:	Compilation of N activity data from farm data statistics	
Documentation:	Results of compilation and results of QA/QC	
Reporting:	Submission of data to Government Agency	
	⇓	
	Governmental Agencies	
Review/Quality assurance:	Country Level inputs of activity data and emission factors	
Internal quality control:	Compilation of national emission inventory	
Documentation:	Results of compilation and results of QA/QC	
Reporting:	Submission of data to IPCC/OECD	
	⇓	
	External review	
External Review:	External audit; stakeholders, peer & public review, verification	
Documentation:	Results of external review	
	⇓	
	IPCC/OECD/UNFCCC Secretariat	
External Review:	Requires standard format and transparency; Ensure consistency with other inventories and external data	

Source: Mangino, 1999

6.1.1 Sources of bias

There are five possible sources of biases, which lead to inaccuracies in emission estimates, i.e. (i) personal biases, (ii) sampling biases, (iii) measurement biases, (iv) data manipulation biases, including guestimation, and, finally (v) fraud, which is consciously introducing biases. These categories of biases are briefly explained below.

Personal biases

Personal biases are the most complex source of biases. The conceptual interpretation of emission inventories and of the proposed methodology to calculate the emissions can vary from scientist to scientist especially when no proper guidelines are provided. In fact, it is the purpose of the guidelines for *good practice* in inventory preparation to overcome this type of bias.

Sampling biases

Emission inventories require census data of agricultural activity data, i.e. of type and number of animals, type and number of AWMS's, and accurate estimates of emission factors for each of these AWMS's. Census data usually consist of a small collection from an aggregate or population. The sample is examined but it is the aggregate or population that interest the users. The sample can be the animals, N excretion rates and AWMS's in a certain areas. Unless samples are representative, facts about the sample cannot be taken as the facts about the aggregate or population. Generally, there is an endless variety among areas and farms so that successive samples are usually different. Hence, the key problem is where and when to sample to obtain representative samples. Evidently, sampling is a large potential source of bias in inventory studies, and proper guidelines are needed. Sampling is also a possible source of bias in investigations that quantitatively estimate the N_2O flux for deriving emission factors.

Measurement biases

Measurements of the amount and N content of animal excretions and of the N_2O concentrations in air require chemical analyses. Potentially, there are a number of artefacts in the chemical analyses that may lead to bias. All these potential artefacts can be minimized by good laboratory practice and by careful calibration of the methods. Inclusion of appropriate standard samples in routine analyses and participation in sample exchange programmes are very useful for identifying and preventing systematic deviations in the chemical analyses.

Data manipulation biases

A potential source of bias is data manipulation, estimating means of replicate analyses and guestimation, which is making estimates (guesses) in the absence of proper data. Generalizations, averaging and upscaling may also lead to loss of information as well as bias. Cross-checks should be made when using spread sheets. Rounding off of figures must be postponed until the last calculation has been performed. Unfortunately, there are no general guidelines, with respect to data manipulation, except for the standardised IPCC work sheets and the application of accepted mathematical rules.

Biases due to fraud

When emission inventories and greenhouse gas budgets are used as control and policy instrument to enforce a protocol with possible economic consequences for countries, it then becomes obvious that some of these countries may try to manipulate the budget so as to minimize the economic consequences. The message presented here is that biases may be larger in the case of greenhouse gas budgets being used as a regulatory control instrument than a management instrument.

6.1.2 Sources of errors

Errors occur as a result of random variations, and show up as variance in repeated determinations. Two types of errors can be distinguished, i.e. sampling and measurement errors. When the precision is low, and determinations are carried out only once, errors and biases merge into each other.

Sampling error

Sampling errors originate from 'within-area' heterogeneity, from spatial variations or temporal variations or both. Animal wastes are notoriously variable in space and time, even within well-defined plots and areas, and require well-designed sampling strategies. Emissions of N_2O are often associated with hot spots and with certain events. As a consequence, frequency distributions of N_2O losses in space and time tend to be highly skewed and the variance becomes extremely large. In such cases, errors are large. Quantification of the sampling error requires repeated sampling following appropriate sampling designs, and repeated analyses.

Measurement error

Measurement errors originate from variations introduced during the determinations of the volume and composition of the sample, i.e. through sub-sampling, pre-treatment and chemical analysis. The measurement error shows up as the variance of repeated measurements of one sample. Usually, the measurement error is much smaller than the sampling error. Good laboratories usually present results of chemical analyses with a relative error of less than 5% for nitrogen in waste and N_2O in air.

Total error in emission estimates

The total variance in the emission inventory is less than the sum of the variances of the individual inputs and outputs because of the covariance between the various items in the work sheets of the emission inventories. The total variance is equal to the sum of the variances of the various items plus twice the covariance of all possible two-way combinations of these items. Because, there is often a negative correlation between the sizes of the various items, the covariance is negative. In statistical terms, the total variance of the budget on the balance is equal to

$$\text{Var (budget)} = \text{var}(\text{animals}_1) + ... + \text{var}(\text{animals}_x) + \text{var}(\text{N excretion}_{1,x}) + ... + \text{var}(\text{AWMS}_{1,y}) + ... + 2\,\text{cov}(\text{animals}_1, \text{animals}_2, ...) + ... + 2\,\text{cov}(\text{animals}_1, \text{AWMS}_1) + ... + 2\,\text{cov}(\text{AWMS}_{y-1}, \text{AWMS}_y).$$

Where:

Animals$_{1,\,x}$: number of animals, a total of x types

N excretion$_{1,\,x}$: amount of N excreted per animal type

AWMS$_{1,\,y}$: emission factor per type of animal waste management system, with y systems

var: estimated variance, and

cov: estimated covariance

The total variance of the emission estimate heavily depends on the size and variance of large items and on the covariance between these major items. If precise information on the variance and covariance is lacking, and one is interested in the possible variance of the total emission estimate, it is recommended to perform uncertainty analysis. This may be done via a Monte Carlo type of simulation, using frequency distributions for the various items based on literature data and best guesses (e.g. Van Aardenne, 2002). Again, proper assessment of the interactions between the various inputs and outputs is crucial for obtaining unbiased and precise estimates of the frequency distribution of the estimates, and hence of errors.

Summarizing, there are a number of possible sources of biases and errors. Biases are generally a more serious problem than errors in emission inventories. They must be prevented in order to preclude incorrect conclusions. It requires in-depth analyses of sources and sinks of N_2O emissions and of its controlling factors as well as testing of assumptions and proper data acquisition and handling. It is therefore the purpose of the *IPCC Guidelines* and *good practice* to minimize biases.

6.2 Default uncertainty for emissions factors

Default emission factors and uncertainty estimates for AWMS's are presented in Table 4-20 of the *IPCC Guidelines*. The uncertainty in these default estimates is large, up to two orders of magnitude. These wide ranges reflect (i) the lack of quantitative data and (ii) the many complicating interactions due to the interference of environmental and management factors. Emissions of N_2O are predominantly the result of the escape of N_2O from the microbial processes nitrification and denitrification. The amount of N_2O emitted depends on the factors that determine the rate of the processes of nitrification and denitrification, and the rate at which the produced N_2O can escape from the AWMS. There are complex interactions and feed backs, which are not completely known. Furthermore, there is a lack of quantitative information about the environmental conditions and the actual management of AWMS in practice.

As discussed before, uncertainty assessment must focus on the uncertainty in the major sources (see also Van Aardenne, 2002). Major sources of N_2O, include the AWMS categories urine and dung droppings from grazing animals, solid storage and drylot, and other systems. The uncertainties presented in Table 4-20 of the *IPCC Guidelines* reflect the possible range of emission factors for individual sources; they do not reflect the uncertainty in the mean emission factor for one country.

7 CONCLUSIONS

On a global scale, animal waste management systems AMWS's are important sources of N_2O. The magnitude of the N_2O emissions is related to the management of the animal waste and to the amount of nitrogen in the animal waste. There is a wide range in animal waste management systems and also in the amounts of N in the animal waste. As a result, emissions of N_2O from animal waste management systems also differ widely.

The *IPCC Guidelines* provide a transparent framework and step-by-step guide to calculate national emissions from animal waste during storage and treatment. *Good practice* in inventory preparation involves a series of six consecutive steps to be made. Crucial steps are the accurate estimation of the total amount of nitrogen in the animal waste per animal waste management system, and the application of the proper emission factors to each of the animal waste management system. Procedures, data acquisition and data handling must be well-documented, and whenever possible only data and emissions factors from peer-reviewed literature should be used.

Though the *IPCC Guidelines* provide a good framework for national N_2O emission inventories, there is still a relatively large uncertainty associated with the estimated total N_2O emissions from animal waste management systems. This uncertainty is mainly related to the uncertainty in the emission factors. A coordinated research action is required to further improve the accuracy of the emission estimates.

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