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Review of methane and nitrous oxide emission factors for manure management in cold climates

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Foreword

This report is the result of an assignment from the Swedish Environmental Protection Agency. It forms part of a larger task being performed by the Swedish EPA on commission of the Swedish government. The larger project is aimed at reviewing and developing the methods used for quantifying the emissions of so-called 'greenhouse gases' from Swedish Agriculture. National emission estimates are submitted annually as part of Sweden's undertaking to the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol.

This report consists of a review of the methods for estimating methane and nitrous oxide emissions from animal manure management. Manure management is one of the emission source categories within the agricultural sector. The estimation and reporting methodologies are based on guidelines laid down by the Intergovernmental Panel on Climate Change (IPCC). The purpose of the review is to establish the appropriateness of the presently used estimation methods for Swedish agricultural and climatic conditions. Default parameters and emissions factors are critically evaluated and, where appropriate, recommendations are offered for improvement. The review was carried out by Andrew Dustan (Senior Research Manager).

Uppsala, April 2002

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Summary

The literature study reported here forms part of an overall objective to review the methods for estimating the greenhouse gas emissions from the agricultural sector. In this report the focus is on the CH_4 and N_2O emissions arising from animal manure management. The IPCC methodology and default parameters are critically reviewed in order to establish their appropriateness under Swedish climatic and agricultural conditions.

There are few reported studies which consider the emissions of CH_4 and N_2O from animal manure storage under climatic conditions corresponding to those in Sweden. Studies based on comprehensive, long-term field measurements are even scarcer. This gives a limited basis for recommending new emissions factors or other parameters. There is, however, support for updating some of the parameter values. The recommended changes are summarised in the table below.

Parameter	IPCC default	Recommended value for Sweden
Volatile solids (VS)		
– cattle	92%	87%
– swine	98%	87%
MCF		
– slurry / liquid	39 %	10 %
– solid	1 %	2 %

Recommendations are offered on the principle that the IPCC defaults are to be kept unless there is reasonable support for deviation from these. This is done despite the observation that, in some cases, the IPCC defaults are themselves not well supported by published literature.

The IPCC methodology consists of a relatively simple model, which aggregates several complex and dynamic influences. An alternate modelling approach has been identified for quantifying methane emissions from slurry systems. This model has a fundamental basis and, with appropriate input information could be employed for estimating Swedish emissions.

Another factor, arising in this review, is the importance of the distribution of animals among the management systems. According to the IPCC criteria a portion of the systems which are currently viewed, in the Swedish Inventory, as ‘Solid’ systems should in fact fall under ‘Liquid/Slurry’ systems. This may have a significant effect on the overall balance of CH_4 and N_2O emissions.

Potentials for improving the accuracy of Swedish emission estimates are identified. The need for studies and field measurements under Swedish conditions is emphasised. Particularly critical areas are: the characterisation of fresh cattle and swine manures, updated estimates for the distribution of manure management systems among so-called ’solid’ and ’slurry’ systems, measurements of methane from stored cattle and swine solid manure, and, measurement of nitrous oxide emissions from slurry systems with straw or natural-crust covers.

Sammanfattning

Denna litteraturgenomgång ingår som en del i arbetet med att kartlägga olika metoder för beräkning av utsläppen av växthusgaser från lantbrukssektorn. Rapporten är speciellt inriktad på CH_4- och N_2O-emissioner vid stallgödselhantering. Den så kallade IPCC-metoden samt de angivna riktvärdena har granskats och prövats med avseende på giltighet för svenska klimatförhållanden och svenskt lantbruk.

Det finns endast ett fåtal studier rapporterade som behandlar emissioner av CH_4 och N_2O vid lagring av stallgödsel i nordiskt klimat eller motsvarande. Ännu mindre förekommer långliggande försök på området. Detta medför att underlaget för revidering av tidigare riktvärden och övriga faktorer är begränsat. Ett visst underlag finns dock och rekommenderade ändringar är sammanfattade i tabellen nedan.

Faktor/variabel	Riktvärden IPCC	Rekommenderade värden; Sverige
Organisk substans (VS)		
– nöt	92 %	87 %
– svin	98 %	87 %
MCF		
– flytgödsel	39 %	10 %
– fastgödsel	1 %	2 %

Rekommendationerna bygger på principen att IPCC:s riktvärden får fortsatt gälla även för svenska förhållanden, om det bedöms att andra uppgifter inte är tillräckligt underbyggda för att en ändring ska föreslås. Denna princip har fått gälla generellt trots att det i vissa fall framkommit att även IPCC:s egna riktvärden har ett begränsat underlag i litteraturen.

IPCC-metoden består av en modell som förenklar beräkningen av ett antal komplexa och dynamiska faktorers nettoeffekt. En alternativ modell har identifierats för kvantifiering av metanemissioner från flytgödselsystem. Modellen bygger på grundläggande principer och skulle kunna användas i beräkningar för svenska förhållanden, om relevanta indata är tillgängliga.

En annan viktig aspekt som framkommit i denna genomgång, är behovet av korrekt statistik över antalet djur i olika hanteringssystem. Med IPCC:s definitioner för olika gödselhanteringssystem borde nämligen en del av fastgödselsystemen i de svenska beräkningarna placeras i kategorin flytgödselsystem. Detta har troligen en signifikant inverkan på balansen mellan CH_4 och N_2O.

Potentialen för förbättring av noggrannheten i de svenska emissionsberäkningarna har identifierats. Behoven av studier och fältmätningar för svenska förhållanden har betonats. Särskilt prioriterade områden är: karaktärisering av färsk nöt- och svingödsel, aktuell statistik över antalet djur inom fast- respektive flytgödselsystem, uppmätning av metanavgång vid lagring av nöt- och svinfastgödsel samt uppmätning av lustgasavgång från flytgödsellager försedda med halmtäckning eller ett naturligt svämtäcke.

Introduction

Background

The Swedish Environmental Protection Agency has been commissioned by the government to submit annual reports on the Swedish emissions of ‘greenhouse gases’ to the EU Commission and to the United Nations Framework Convention on Climate Change, UNFCCC. Emission reports, in the form of national inventories, follow guidelines set up by the Intergovernmental Panel on Climate Change, IPCC.

The national inventory includes total emissions estimates for a variety of gaseous compounds which are considered to affect climate change and thus termed ‘climate gases’ or ‘greenhouse gases’. The IPCC has recommended that, of these, the direct greenhouse gases (CO_2, CH_4 and N_2O) should be given the highest priority. Anthropogenic activity is categorised into a number of sectors and emissions for each of these sectors are estimated and reported in the inventories. In this review the emissions within the agricultural sector are of interest. The focus is further narrowed to consider only the emissions associated with animal manure management.

According to the estimates of the Swedish Inventory for 1999 (SNV, 2001) the agricultural sector was responsible for CH_4 emissions of 161 Gg i.e. 55% of the total national emissions. Corresponding figures for N_2O are 13.6 Gg or 58% of the national total. ‘Manure Management’ accounts for 14.3 Gg of CH_4 and 1.9 Gg of N_2O. Placed in the perspective of national emissions then, emissions from manure management account for about 4.8% of the total CH_4 output and 8.3% of total N_2O emissions.

When comparing the magnitude of the various emissions it is worth considering them in terms of their global warming potential (GWP). The GWP (over a 100 year period) of CH_4 is 21 times higher than an equivalent mass of CO_2. For N_2O the GWP is 310 times higher than an equivalent mass of CO_2 (Houghton, 1996). Thus, from manure management, nitrous oxide is responsible for about 67% of the GWP and methane for about 33%.

Description of Assignment

The government has commissioned the Swedish EPA to, in consultation with the Swedish Board of Agriculture, review the methods for estimating the greenhouse gas emissions from agriculture. The literature study reported here forms a part of this overall objective. The focus, in this review, is narrowed to the CH_4 and N_2O emissions arising from ‘manure management’ i.e. the storage and handling of animal manure from animal houses.

The aim of this literature review is to evaluate the appropriateness, under Swedish conditions, of the suggested IPCC default parameters and emission factors within the category of ‘Manure Management’. Where IPCC defaults are found to be unsuitable, updated estimates, supported by literature, are recommended.

Scope

Greenhouse gas emissions from ’Manure Management’ are considered to be methane and nitrous oxide emissions, which result from manure in animal houses and during handling and storage of animal manure. Once the manure is applied to soils, or other uses, the emissions are accounted for within different source categories. Similarly, the manure from animals in pasture is not considered in this review.

In Sweden the manure production is dominated by cattle and swine and it is therefore practical that the review is focussed on these sources. Consideration is given, as far as is possible, to those factors within manure management which are central for CH_4 and N_2O emissions, i.e. climatic conditions, storage periods and manure management systems.

This review starts with a look at the IPCC methodology for emissions estimates from manure management. The Swedish inventory, based on this methodology is also discussed briefly. This overview of the methodology provides some guidance as to which components are of most importance within the overall inventory.

The key components of the emissions estimates are then reviewed separately. These consist of estimates of the quantities and relevant physical characteristics of the manure produced. The waste management systems are also considered. The emissions factors for methane and nitrous oxide generation are then considered in separately. These factors are central to the overall estimate yet are the most uncertain of all the components in the methodology. The focus of the review of emissions factors is on establishing their relevance for Swedish agricultural and climatic conditions.

The review is concluded by a brief summary of the relevance of the IPCC methodology and default parameters to Swedish conditions. The conclusions also highlight any support which can be found for deviating from the IPCC defaults. Recommendations are made for changes to future estimates as well as for studies aimed at addressing the most critical gaps in present knowledge.

IPCC Methodology and the Swedish Inventory

Manure Management and the IPCC

The IPCC Agriculture module (IPCC 1996a, and 1996b) considers five distinct greenhouse gas emission sources - one of these is ‘Domestic Livestock’. ‘Enteric Fermentation’ and ‘Manure Management’ are then subsets of this category. In this review, consideration is limited to ‘Manure Management’ where only CH_4 and N_2O emissions are of interest.

Different levels of detail are possible for the emissions estimates. The choice of appropriate level is guided largely by the availability of appropriate input data. In general, greater levels of detail are encouraged for those activities giving rise to substantial emissions. Conversely, there is little motivation for completing detailed estimates for the minor sources. In concept the different levels of detail follow a similar approach. A range of different source categories is defined, and, for each of these a scale of the activity is estimated, usually in terms of the animal population in each category. This is then multiplied by an ‘emission factor’ which is the estimated emission per animal per year. Thus the total emission is obtained for each source category.

At the most basic level, known as the ‘Inventory Method – Tier 1’, the only inputs required are animal population data. IPCC default emissions factors are used to complete the estimates. The Tier 2 method approaches a greater level of detail by considering more subcategories in terms of the different ‘Animal Waste Management Systems’ (AWMS). More detail is also considered in the estimates of the amount of manure produced in each source category as well as the characteristics of the manure. Beyond Tier 2, greater resolution can be achieved by using locally available information, which takes account of animal sizes, diets, and factors that affect the generation of emissions.

Methane emissions

The discussion below, regarding the Swedish Inventory, identifies the Tier 2 method as being of prime interest for methane emissions from manure management. According to the Guidelines the total emission from each animal category is:

$$\text{emission}_i = \text{EF}_i \text{ x population}_\text{i} \qquad \text{(eq. 1)}$$

where: i denotes each animal type

EFi is the annual emission factor (kg CH4/year) for each animal type, i, and,

$$\text{EF}_i = \text{VS}_i \text{ x 365 days/yr x B}_{oi} \text{ x 0.67kg/m}^3 \text{ x } \sum_{jk} \text{MCF}_{jk} \text{ x MS\%}_{ijk} \qquad \text{(eq. 2)}$$

where: VS_i is the daily volatile solids (kg) excreted for animal type i

B_{oi} is the maximum methane producing capacity (m^3/kg of VS) for manure produced by animal type i

MCF_{jk} is the methane conversion factor for manure management system *j* in climate region *k*.

$MS\%_{ijk}$ is the fraction of animal type *i*'s manure handled using manure system *j* in climate region *k*.

In the IPCC recommended defaults for the methane conversion factor, MCF, distinction is between three climate categories. These categories of 'Cool', 'Temperate' and 'Warm' correspond to climates with annual mean temperatures of less than 15°C, 15 to 25°C, and above 25°C respectively. Other than the MCFs, there is no explicit dependence on temperature in any of the other IPCC default parameters. Certain defaults, such as methane generation potential or volatile solids content, are broadly categorised by geographical location. The differences in these parameters are, however, more likely a result of animal diet and other management factors than of climate specifically.

Reference is made to the IPCC Manual (1996b) for a more detailed description of the application of eq. 2 and of the various default values. The above equation highlights the components of the methodology that are of interest in this critical review. These are discussed separately in subsequent sections.

Changes to the IPCC Methane Conversion Factors

In the IPCC Good Practice Guidance (2000) some of the methane conversion factors were updated from the values appearing in the Revised 1996 Guidelines (IPCC, 1996a and 1996b). Some new waste systems were also added.. The relevant values for Swedish conditions, in 1996 and the updated values and systems in the Good Practice Guidance (2000), are summarised in Table 1.

Table 1. Methane Conversion Factors (MCF) relevant to Swedish conditions according to the IPCC 1996 and 2000 methodologies

Source	Waste System	MCF* (cool climate)
Revised 1996 Guidelines: Reference Manual	Solid	1 %
	Liquid/Slurry	10 %
Good Practice Guidance, 2000	Solid	1 %
	Liquid/Slurry	39 %
	Deep litter (cattle and swine)	39%

* for storage periods > 1 month

In the Good Practice Guidance (IPCC, 2000), no references are given to support the substantial increase in the MCF from 10% to 39%. The origin of this change is given as "Judgement by Expert Group". In an attempt to investigate the origin of this the IPCC technical support unit (TSU) was contacted – they in turn recommended contact with certain members of the Expert group. However, no response was forthcoming from any of the members or the co-chairs contacted (via email). The methane conversion factor is discussed in depth in a separate section of this review.

Nitrous oxide emissions

According to the IPCC guidelines (1996b), a single calculation formula is given for N_2O emissions:

$$N_2O_{(AWMS)} = \sum \left[N_{(T)} \times N_{ex(T)} \times AWMS_{(T)} \times EF_{(AWMS,T)} \right] \qquad \text{(eq. 3)}$$

where: (AWMS) refers to the Animal Waste Management System

$N_2O_{(AWMS)}$ is the N_2O emission from a particular AWMS

$N_{(T)}$ is the total number of animals of type T

$N_{ex(T)}$ is the N excretion from animals of type T (kg N/animal/yr)

$AWMS_{(T)}$ is the fraction of $N_{ex(T)}$ from for the type of AWMS containing animals of type T

$EF_{(AWMS,T)}$ is the N_2O emission factor for an AWMS (kg N_2O-N/kg N_{ex} in the AWMS) of animals of type T.

The accuracy of the above estimate may be improved by using relevant local values, instead of IPCC defaults, for the components $N_{ex(T)}$, $AWMS_{(T)}$ and possibly even $EF_{(AWMS,T).}$

Default emissions factors for nitrous oxide are **independent of climate**. For the manure management systems relevant in Sweden, the IPCC default emission factors for N_2O are shown in Table 2.

Table 2. IPCC nitrous oxide emission factors

AWMS	Emissions factor (kg N_2O-N/kg N_{ex})
Solid Storage	0.02
Liquid Slurry	0.001
Deep Litter (category added in IPCC, 2000 for cattle and swine)	0.02

Swedish Inventory

The basis of Swedish application of the IPCC methodology is laid out in Sweden's National Inventory Report (SNV, 2001). Local activity information, regarding animal populations, in various categories and waste management systems, originates from information published by the Swedish Board of Agriculture and Statistics Sweden (SCB). This is considered to be good quality data.

For methane emissions from cattle and swine the Tier 2 method is used and for all other animal categories the Tier 1 approach is used. The focus on cattle and swine is motivated by the fact that these, together, account for 85-90% of the methane emissions from manure management. IPCC default values are used for methane generation potential (B_o) for all manure types, and the methane conversion factors

(MCF) for cool climates. A volatile solids (VS) content of 92% VS/dry matter is assumed for all manure types.

The quantities of manure produced, per animal, in each animal category are based on values reported by the Swedish Board of Agriculture (SJV, 1993 and 1995 for pigs and cattle respectively).

For nitrous oxide emissions, Swedish activity data is used with IPCC default emissions factors. The nitrogen content of the manure, N_{ex}, for each animal category, is also taken from the above mentioned reports (SJV, 1993 and 1995).

In eq. 2 and 3, the annual production of manure are adjusted to reflect the period in which the animals are kept indoors i.e. when they are not in pasture. Statistics for this stable period are also available (e.g. SCB, 2000). The remainder of the manure produced is presumably excreted to pasture and is accounted for in a separate source category.

Review of Key Components for Emissions Estimates

It is clear from the form eq 2 and 3 that inaccuracy in any of the individual components will results in a proportional effect on the overall emission estimate. It is thus necessary to review each component and identify those in which there is low confidence, with particular consideration being given to the relevance under Swedish conditions. In this section the various components are discussed under the headings of ’waste characteristics’ and ’waste management systems’. The uncertainty related to the emissions factors is also discussed while literature on the methane conversion factor and nitrous oxide emission factor is considered in separate respective sections.

Waste Characteristics

There are various characteristics of the manure that will affect the amount of methane or nitrous oxide emitted. These characteristics may change substantially throughout the storage period as a result of various chemical and microbial processes or due to drying, drainage or precipitation. The effects of these changes on the emissions are implicitly included in the methodology, which considers the overall process. It should thus be noted that in order to establish a common basis for the emissions estimates it is the **fresh manure characteristics** that are of interest. This means that caution is needed when using data from stored manure or where the sample history is unknown.

Excreted Nitrogen and Manure Production

The sources of information (SJV, 1993 and 1995) for manure production and excreted nitrogen, N_{ex}, were mentioned above with respect to the Swedish Inventory. Data for swine manure (SJV, 1993) has recently been updated (SJV, 2001).

The manure production and nitrogen contents reported in the SJV reports are based on calculations, which in turn include a number of assumptions regarding material constants, animal metabolism etc. It is not clear from the reports (SJV 1993, 1995 or 2001) to what extent the accuracy of these calculated values has been evaluated. However, the reported data on manure production and nitrogen content are used as inputs to the STANK model. This model, which is maintained by the Swedish Board of Agriculture, is used as an aid for nutrient and manure management in Sweden. This is a working model that is subject to independent evaluation and update. As a result, no further review of the estimates for N_{ex} or manure production is offered here. However, these variables are flagged as sources of uncertainty.

Volatile Solids

The volatile solid content, VS, is the driving variable for methane production from manure. Sommer et al. (2002a) argue that it is also central to N_2O production although this dependence is not included in the IPCC methodology for N_2O. The volatile solids of manure from an animal category will vary with diet, and other factors such as straw addition. As a result of the sensitivity of VS production to management practices, the Good Practice Guidance (IPCC, 2000) encourages the use of country-specific, published data for VS. In the absence of such data the default values relevant to Sweden would be 92% VS/DM for cattle and 98% for swine manure (*DM= dry matter*).

The Swedish National Inventory uses a value of 92% for all cattle and swine animal groups. In the Swedish Inventory an RVF report (1996) is cited as suggesting VS/DM values of 89% for cattle and 88% for swine manure. This is used to support the use of the value of 92% for all cattle and swine categories. However, the above values for VS content are higher than most of those suggested in the literature, for the different manure types. The RVF report mentioned above, in turn sites a much older source, Solyom (1978), for the VS estimates. Subsequent to this though there have been several reported measurements of VS for different animal manure types and under Swedish conditions. Thyselius (1982) presented the following values for VS/DM:

> Cattle manure 78%, with 2% straw 81.5% and with 4% straw 82.8%
> Swine manure 84.1%, with 2% straw 81.9%.

In a more recent study of biogas production at Jälla, cattle manure slurry consisted of 10.6% DM and 8.8% VS, this translates to 83.3% VS/DM (Edström 2002).

Additional Swedish studies (e.g. Norin 1996, Thyselius 1986, Nordberg and Edström 1997) report VS values in the 78 to 82 % range.

The report of Steineck et al. (1999) presents a comprehensive study of manure characteristics from Swedish agriculture. The data represent measurements from 108 manure samples taken from conventional and ecological production from Skåne in the south to Norrland in the north. Table 3 below shows the VS values calculated as the difference between the dry matter, DM, and the ash content.

Table 3. Volatile solids, VS, for Cattle and Swine Manure (Steineck et al., 1999)

	Cattle				Swine	
	Ecological		Conventional		Conventional	
	solid	slurry	solid	slurry	solid	slurry
DM (% FM*)	18.0 ±3.5	7.5 ±1.8	16.6 ±1.7	9.8 ±2.2	23.8 ±3.9	8.8 ±3.4
Ash (% of DM)	16.7 ±5.1	16.2 ±2.7	12.7 ±1.8	15.7 ±2.3	20.4 ±4.5	19.3 ±3.0
VS (% of DM)	83.3 ±5.1	83.8 ±2.7	87.3 ±1.8	84.3 ±2.3	79.6 ±4.5	80.7 ±3.0

*FM: Fresh Manure

Even outside of Sweden substantially lower VS values are reported than the IPCC defaults. Using mean values of the measured ranges reported by Callaghan et al. (2002) yields VS/DM values for cattle manure around 75% - this study from the UK. In a Danish study, reported by Husted (1994) the following VS/DM values are presented:

> Cattle slurry 73.3%, cattle solid manure 76.2%
> Swine slurry 61%, swine solid manure 78.8%

Associated with most of the above VS concentrations are unknown effects of previous storage time and straw addition relative to fresh animal manure. In a personal communication Gustafson (2002) reported the following values for fresh manure samples taken directly after excretion (from a Swedish farm): for growing steers and lactating cows the ash contents were 14% and 13% (of DM) respectively. This implies VS concentrations of 86-87%. No corresponding values could be found for Swedish swine manure.

The above values (86-87%) are fairly close to the value for solid manure from conventional cattle farming listed in Table 3. This tends to indicate that, at least for solid cattle manure, the storage period prior to sampling did not significantly affect the VS levels in the study of Steineck et al. (1999). For swine manure the situation may be slightly different since more straw is generally added. This, by itself, may affect the VS levels somewhat, but it also changes the conditions for methane generation due to the heat production during composting (as discussed later in this report). However, it seems unlikely that the VS could drop from the 98% suggested by the IPCC to the 81% suggested by Table 3. If one takes the highest of the VS contents reported in Table 3 for swine manure, i.e. 80.7 + 3% the result (say 84%) is still at the high end of the values reported in all of the above studies. It is thus argued here that a VS concentration of 87%, such as is applicable to cattle, is still a conservative (over) estimate for fresh swine manure.

There appears to be a need to perform more extensive sampling and characterisation of fresh manure from cattle and swine in Sweden. In a further stage of development, the fresh manure values could be adapted for the addition of straw in various management systems. The VS in straw does, however, impact differently to manure-VS when it comes to methane generation; this is discussed further with respect to methane generation potential below. Until more local data are available a value of VS/DM content of 87% is recommended for both cattle and pig manure.

Methane Generation Potential

The quantity, B_0, in eq. 2 represents the maximum quantity of methane that can be produced per mass of VS. It is also known as the biological methane potential (BMP). B_0 may be determined by performing anaerobic fermentation of the material, in a laboratory, over long periods of time, usually over 90 days (Steed and Hashimoto, 1994). The methane produced per quantity of VS is the B_0 value of the material. The ultimate methane yield is reportedly independent of temperature (Safley and Westerman, 1990). B_0 for manure is, however, dependent on the chemical composition of the VS (Sommer et al., 2002a). Thus the animals' diet is important, so is the amount and type of straw or bedding added.

The Swedish Inventory makes use of the IPCC defaults. According to the Reference Manual (IPCC, 1996b), $B_0 = 0.24$ m^3 CH_4/kg VS for dairy cattle manure, 0.17 m^3 CH_4/kg VS for-non dairy cattle and 0.45 m^3 CH_4/kg VS for all swine categories.

The Swedish data, which could be found on B_0 values, originates mainly from biogas related studies. These, however, are usually based on manures of unknown history (age) or mixtures of different manure types or organic materials. These values are thus of little significance here.

Safley and Westerman (1990), after reviewing the literature, list B_0 values from several studies. These values are for swine, beef cattle and dairy cattle and include a description of the ration type. The values reported in that review are consistent with the range of IPCC values cited above. This is no coincidence since as the work of Safley, particularly Safley et al. (1992) was significant in the establishment of the IPCC default values.

Husted, (1994) quote values from Hashimoto et al. (1980) and Hashimoto (1984) for potential methane production from cattle and swine manure of 0.21 m^3 CH_4/kg VS and 0.51m^3 CH_4/kg VS respectively.

In a Danish study Hansen et al. (1998) report potential biogas yields for cattle and swine manure of 0.285 and 0.3 m^3 CH_4/kg VS respectively. These are in reasonable agreement with the values estimated by Sommer et al. (2001b and 2002a) of 0.22 and 0.32 m^3 CH_4/kg VS, for cattle and swine respectively.

Sommer et al. (2001b and 2002a) emphasis the importance of the composition of the VS for determining the methane yields. The main components of VS are fats, proteins and carbohydrates. The fats and proteins and a portion of the carbohydrates are readily degradable. However, a significant portion of the carbohydrates (e.g. lignocellulose) is relatively resistant to degradation and is only partially, or slowly, broken down. Table 4 shows the estimates of Sommer et al. (2001b and 2002a) for the distribution of volatile solids in cattle and swine manure slurry. Based on this composition, the methane generation potential was estimated using Bushwell’s equation. In Table 4 this potential is reported on the basis of the degradable volatile solids, VS_D. This is seen to be significantly higher than the estimated B_0 value based on the total VS.

Table 4. Composition of VS and resulting methane generation potential (Sommer et al., 2002a)

	Cattle slurry	Swine slurry
Degradable VS_D		
% fat	9	10
% protein	18	30
% carbohydrate	21	25
Degradation-resistant VS, carbohydrate (%)	52	35
B_0’ m^3- CH_4/kg VS_D	0.48	0.50
B_0 m^3- CH_4/kg $VS_{(total)}$	0.22	0.32

The value of B_0’ is reported on a methane volume basis. This is converted from a mass basis using the same assumptions as those used by Sommer et al. (2001b) i.e. a volume of 22.4 l/mol for methane, which gives a conversion factor of 0.71 kg/m^3 CH_4. This is slightly different to the factor of 0.67 kg/m^3 CH_4 used by the IPCC (1996b).

There is significant spread in the estimates of B_0 reported in the literature (cattle manure 0.17 to 0.285 m^3/kg ; swine manure 0.3 to 0.51 m^3/kg). This is likely to be a result of the dependence on diet and straw content, which vary significantly from farm to farm but primarily from country to country. Since these are systematic dependencies there is little point in merely gathering more published values of B_0. What is required is knowledge of the VS composition and its relationship to B_0. Thus there appears to be a need, in Sweden, for more comprehensive investigation of fresh manures with respect to VS composition and resulting methane generation potential.

Waste Management Systems

There are several different categories of manure management system listed by the Good Practice Guidance (IPCC, 2000). Of these, the following are relevant for methane and nitrous oxide emissions from cattle and swine manure in Sweden: Liquid/Slurry systems; Solid Storage; Deep Litter.

Separate categories exist for manure composting and anaerobic digestion. Although these manure treatments are found in Sweden, and are even increasing in activity, they still represent a very small fraction of the total manure handling and are thus neglected.

Table 5 below (SCB, 2000), shows the distribution of animals among the main manure systems in Sweden. This indicates that for cattle and swine the dominant systems are the solid and (covered) slurry systems. This is worth considering when investigating emission factors for the various systems.

The IPCC does not make divisions shown in the Table 5, between ‘solid’ and ‘semi-solid’ systems or slurry systems ‘with’ and ‘without’ covers. Later discussion in this review indicates the importance of information regarding surface covers in liquid/slurry systems. Of the covered slurry tanks in Sweden, 90% make use of the natural crust that forms on the slurry surface.

Table 5. Number of animals in each Swedish manure management category (SCB, 2000)

A - Solid manure on solid base with retaining wall
B - Solid manure on solid base with no retaining wall
C - Semi-solid manure on solid base with retaining wall
D – Slurry without cover
E - Slurry with cover
F - Deep litter system
G - Other method

Animal category	Number in category [a]	% of animals per management system						
		A	B	C	D	E	F	G
Dairy cattle	425 329	41	3	3	13	39	1	0
Non-dairy cattle	1 191 971	47	7	3	6	20	16	1
Breeding swine	218 209	58	5	3	4	22	7	1
Fattening pigs	1 126 102	15	2	0	19	61	1	1

[a] Statistics for December 2001 (SCB, 2002)

In the Swedish Inventory of 1999 (SNV, 2001) ‘semi-solid manure’ (kletgödsel) is considered in the ‘solid-manure’ (fastgödsel) category. According to the IPCC (2000), for nitrous oxide emissions, the division between solid and slurry systems is at 20% dry matter. This division is presumably made on the basis of the predominance of aerobic or anaerobic conditions in the manure. No corresponding division could be found in the IPCC methodology in respect of methane emissions.

Two point are emphasised here with regards to the distribution between ‘solid’ and ‘slurry/liquid’ systems:

1. Traditionally the definition of a semi-solid manure is that it can neither be pumped or stacked. This usually translates to a solid content of around 12-20% dry matter (Steineck et al., 2000). According to this IPCC definition, all semi-solid manure should now be categorised as ‘liquid/slurry’, at least if the categories should reflect conditions for nitrous oxide formation.
2. The distribution of storage systems shown in Table 5 is based on questionnaires completed by farm owners. It has been observed (Karlsson, 2002) that some systems originally built as solid systems continue to be classified as ‘solid’ even though they may contain manure fulfilling the definition of ‘semi-solid’. There has been a tendency toward wetter cattle manures, partly as a result of the increased winter feeding of cattle with silage. This tendency is, however, not reflected in the reported statistics. It is thus suspected that the percentage of ‘semi-solid’ systems in Table 5 should increase, at the expense of ‘solid’ systems.

Redistribution of the AWMSs according to the IPCC division between ‘solid’ and ‘slurry/liquid’ systems could have a significant impact on the overall inventory. If the same division criteria (20% DM) is applied for methane, this would mean that the estimated methane emissions would increase and the nitrous oxide emissions would decrease. This would give an overall decrease of emissions in terms of the global warming potential.

There is apparently a need for more comprehensive Swedish data on the distribution of animals among the various waste management systems. Before this is attempted though, more meaningful criteria for the division should be established. As will become apparent in later discussion, a dry matter content of 20% is insufficient as an indicator of whether a manure store will be predominantly anaerobic or aerobic.

Other points of emission

This review considers only the emissions during the storage of manure. Other activities, which could also be considered under ‘Manure Management’, are the emissions from manure inside animal houses and the emissions from the spreading of the manure. Subsequent emissions from fields are considered in a separate module in the IPCC methodology.

A typical example of manure stored inside animal houses would be the underfloor storage of slurry in slatted floor systems e.g. Jungbluth et al. (2001). In Sweden however, the occurrences of slurry in channels or basins inside the animal houses is rare and slurry or solid manure is removed usually within one day of excretion. The exception being deep litter where the manure is allowed to build up in the animal houses with occasional addition of straw as a bedding material and periodic removal of the litter. Deep litter is however considered as a category on its own. For all other systems, the short storage periods in the animal houses imply that this does not need to be considered as an extra stage or source of emissions.

Not much literature could be found regarding the emissions from spreading itself. However, we know that biological processes produce CH_4 and N_2O. These processes do not usually respond instantaneously to changes in environmental conditions – such as those accompanying manure spreading. Thus increased emissions during spreading itself could only be the result of the liberation the relatively small quantities of gas trapped in the manure, or dissolved in the slurry. This is quite different to the release of ammonia, for example, whose volatilisation is affected by a number of chemical factors during spreading. Increases in methane concentration have been recorded during the stirring up of slurries and pumping-out operations, which would release some of the trapped or dissolved gas (Kaharabata et al., 1998). The period of release for these activities is, however, so short that in terms of the overall emission such disturbances to the slurry can be neglected.

Emissions Factors – Basis and Uncertainty

The components of the estimation methodology, discussed above, are relatively easily measured physical characteristics of the systems and materials. For methane, the methane conversion factor, MCF, is used to complete the estimation of the emissions factor. The MCF describes how much of the potential methane generation actually results in methane emissions. For nitrous oxide, the emissions factor EF_{nit}, denotes the fraction of excreted nitrogen which is emitted from manure as nitrous oxide. These factors (MCF and EF_{nit}) are themselves an aggregation of several different and in some cases dynamic influences. These include:

- The effects of temperature and seasonal temperature variation. More discussion of this important point follows.
- The stable and storage periods are not explicitly accounted for although, presumably, the IPCC default values are aimed at some ‘typical’ annual operation pattern. It is not apparent though, what this basis may be and significant differences in manure storage cycles are likely to occur from country to country. Husted (1994) suggests the previous Danish inventories significantly overestimated annual methane emissions because seasonal variations in emission rates and seasonal variations in stored manure volume were neglected.
- Storage conditions are accounted for only by the division into the different AWMSs discussed previously. No account is made for additional factors that may affect emissions such as surface covers on slurry tanks, moisture content in solid waste storage etc.
- The IPCC method is essentially a static estimate based on some integrated rate of methane or nitrous oxide production over an entire year. Thus there is no account of the dynamics associated with storage periods in which there is seasonal temperature change and a reduction in emission rate as the VS or nitrogen content in the manure decreases with time.
- The nature of the manure is not considered beyond the VS content and B_0 (for methane emissions) and N_{ex} (for nitrous oxide emissions). The form of VS and the N_{ex} and even their interrelation may have a significant effect on the underlying gas generation processes (Sommer et al., 2002a).
- Practices of straw addition vary greatly and affect the composition of the substrate and dictates to a large extent whether stored solid manures will be aerobic or anaerobic and if composting will be significant or not.

The complexities noted above mean that the IPCC approach is, necessarily, a vast simplification of reality and significant deviation from the actual emissions may result.

The production of methane and nitrous oxide from animal manure occurs via bacterial process. The activity of the bacteria and thus their productivity is affected by temperature. However, there is relatively little in the IPCC methodology which reflects this temperature dependence. Methane conversion factors differentiate between three climatic zones. Sweden falls under the so-called ‘cool climate’ for regions with a mean temperature below 15°C. It may be questioned if these MCFs are appropriate for Sweden. In southern Sweden, where the majority of agriculture occurs, the mean annual temperature is just under 7.5 °C (as a 10 and 30 year average, SMHI, 1999). Additionally, manure stores may be covered by ice and snow for several months of the year. No studies could be found which investigate how this may affect the CH_4 and N_2O emissions.

A review of published literature reveals a very weak basis for either supporting or adapting the IPCC default values for the MCF or EF_{nit} for cold climates. Many references are made from the IPCC documents and from other literature to ‘expert opinion’, ‘verbal communication’, unpublished reports or literature in various languages, which could not be obtained within the confines of this review.

Additionally there is difficulty interpreting those emission measurements reported in the literature:

- Jungbluth et al. (2001) point out that, to start with, there is a scarcity of data from measurement of greenhouse gas emissions from animal houses and manure stores. Further, they observe that the requirements of continuous measurements over sufficiently long periods of time are not fulfilled in about 80% of the published studies.

- Different bases are used. Emissions are often reported on a basis of ‘per manure store’, ‘per surface area’, or ‘per gain in live weight’ or per ‘slurry volume’ (e.g. Jungbluth et al., 2001; Clemens et al., 2001). These cannot be converted to the common units of interest since the required data (manure volumes, DM or VS content etc.) are missing.

- Gas emissions from animal houses and manure storage are prone to both diurnal and seasonal variations (e.g. Husted, 1994; Kaharabata et al., 1998). This poses some challenge to measurements in the field, which are intended as the basis for estimates of overall emissions factors.

- Much of the published literature is relevant for higher temperatures or for waste systems not widely used in Sweden e.g. lagoon systems and digesters. In these processes, the organic loadings and hydraulic residence times are controlled. These contrast with the low temperature, organically overloaded conditions of typical manure storage.

- Laboratory results are difficult to meaningfully scale up to field scale conditions where there are different volume to surface ratios, bacterial populations etc. (Külling et al., 2001; Jungbluth et al., 2001).

- Nitrous oxide concentrations are often so low that emission estimates cannot be made reliably (Jungbluth et al., 2001; Phillips et al., 1997).

An attempt was made in this study to compile a summary comparison of emission rates from various studies. Due to the above difficulties a number of assumptions had to be made to achieve a common basis. The resulting figures in many cases were completely unreasonable e.g. methane yields exceeding the overall methane potential. Despite these difficulties there is some literature which provides valuable input for a critical discussion of the IPCC defaults. These are considered separately below, in the context of the methane conversion factor and the nitrous oxide emissions factor.

Methane Conversion Factors

Parameters which Influence Emissions

Effects of temperature

Methane is produced by the anaerobic breakdown, or digestion, of organic material by methanogenic bacteria. The bacterial activity is closely related to temperature and different types of bacteria have adapted their activity to different temperature ranges. Thermophilic bacteria operate in the range 45-60°C, mesophilic bacteria in the range 20-45°C and psychrophilic bacteria below 20°C. Although methane production decreases significantly at low temperatures, methanogenesis has been reported at temperatures as low as 4°C (Stevens and Schulte, 1979, cited by Safley and Westerman, 1990). The temperature dependence of methane generation has been well studied, however, data under psychrophilic conditions are less common.

Methane generation is a bulk process (Phillips et al., 1997, Sommer et al., 2000) which is why the methane generation rate should be related to the bulk manure temperature and volume. In slurries, Husted (1994) reported good correlation between the bulk manure temperature and the temperature of the ambient air. Greater differences between bulk and air temperatures occurred during winter with slurry being somewhat warmer than ambient temperature. It was suggested that heat transport from ground prevented slurry temperature from dropping below 4 °C despite ambient temperatures of –4.2 °C. Sommer et al. (2000) correlated methane generation to the slurry temperature 30 cm below the surface. Autumn measurements were conducted as air temperatures declined from 10 °C to 0 °C and slurry temperature declined from around 13 °C to 5 °C depending on the type of surface cover.

At low temperatures, a linear dependence of the methane generation rate is reported in some studies (Sharpe and Harper, 1999; Kaharabata el al., 1998). Other studies report an exponential dependence of methane emission rate on temperature (Husted, 1994; Khan et al., 1997; Sommer et al., 2000). This exponential dependence may be formulated in terms of the Arrhenius equation which is commonly used to describe the dependence of biological processes on temperature e.g.

$$\ln \mathrm{P} = -E_a/\mathrm{RT} + k \qquad \text{(eq. 4)}$$

where P is the production rate, E_a is the activation energy, R the universal gas constant, T the temperature (K) and k a constant. The values of the E_a and k in eq. 4 are dependent on manure character and may be determined from experimental data. Sommer et al. (2002a) present an even more fundamental form of eq. 4 and quantitative estimates of the associated constants for cattle and swine manure. More discussion of their model is offered below with respect to methane emissions from slurry systems.

For solid manures the temperature effects are somewhat more complex. If there is sufficient oxygen supply to the manure, composting processes may generate heat. In the parts of the solid manure which are well supplied with oxygen, not much methane is produced. However, these aerobic zones may heat up the anaerobic zones which generate methane. For example, Husted (1994) reported that composting in the aerobic zone of manure heaps significantly increased the methane production in the anaerobic parts of the manure by the generation of heat. In these cases, the manure temperature does not correlate to the ambient temperature and the effect of climate is reduced. If however, no composting occurs, then manure temperatures are not far from ambient temperatures (Forshell, 1993; Petersen et al., 1998).

Effects of slurry surface cover

Under conditions similar to those in Sweden there seems to be some consensus that surface covers reduce the methane emissions relative to open surface slurries.

Husted (1994) carried out long-term measurements of methane emissions from cattle and pig slurries. He estimated that for pig and cattle slurries, a natural surface crust reduced methane emissions by factors of 10.9 and 12 respectively relative to uncovered slurries. Emissions were observed to increase significantly during periods when no natural surface crust was present. As temperatures increased, the effect of the surface crusting became less significant. During winter the crusts were wetter and more compact compared to the summer months and were more effective in reducing emissions. The lower permeability of the crusts in winter was used to explain the lower emissions.

Sommer et al. (2000) report that methane emissions from manure slurry was reduced by an average of 38% as a result of surface covers. They investigated methane and nitrous oxide emissions from uncovered slurry and slurries covered with a natural surface crust, leca clay pebbles, or straw. Lowest methane emissions were from the slurry covered with straw. The reduced emissions resulting from the surface crusts are explained by the biological oxidation of CH_4 to CO_2 as the gas passes through the porous surface layer.

The effects of surface crusts and covers could also be responsible for some the variation in emissions reported in the literature. The appearance and disappearance of natural crusts or their degree of permeability are not usually reported or related to the emission profiles. Sommer et al. (2000) suggest that a significant part of the methane emissions escapes from cracks and openings in the surface crust. This could give rise to misleading results when small chambers are used for measurement. For example, Husted (1994) used chambers covering slurry areas of 0.14 m^2. This would result in high spatial variability in the measurements. This may be part of the explanation for the relatively high methane emissions reported, by Husted, for swine slurries (see Table 6).

The IPCC default MCFs do not take account of the effects of surface coverings. This can be expected to be a primary source of deviation from MCFs, which are derived from open surface systems (such as lagoons), or from laboratory tests.

Other influences

Other than the influence of temperature and surface crusts on slurries there are several other factors which may influence the effective methane conversion factor, these are discussed below.

Storage cycles – In the study of Husted (1994), manure is added to the manure store during autumn and winter. In April, 75% of the annual turnover is applied to the field. In June the remaining 25% is applied. In the case of cattle slurry Husted presents, as an example, that overall methane emissions would increase by 61% if the slurry were applied in September instead of June. This would be due to the increased storage period at the higher summer temperatures.

Rainfall - Kaharabata et al. (1998) report a tendency for higher fluxes of methane from slurry tanks to be associated with rainfall events. Their hypothesis is that this is a result of the mechanical agitation of the slurry surface increasing the surface for exchange and release of CH_4. A reduced atmospheric pressure is also raised as a possible explanation for this observation.

Diurnal variation - Khan et al. (1997) make the observation that if the diurnal variations in methane emission are ignored, overall emissions are likely to be miscalculated. Kaharabata et al. (1998) also report daily variations with lower methane emissions at night, possibly related to reduced wind speed and hence slightly increased diffusional resistance. Thus estimates based on daytime measurements alone would give substantial overestimates of the total emission.

Straw addition - the addition of straw to solid manure or slurry may result in higher CH_4 emissions due to the input of carbon (Clemens et al., 2001). Although, Husted (1994) reports that straw decomposes slowly under anaerobic conditions.

The major effect of straw addition is its impact on the oxygen supply and thus on the balance between aerobic and anaerobic volumes. Kirchman (1985, cited by Petersen et al., 1998) identified three storage conditions for solid manure: anaerobic fermentation, aerobic and anaerobic decompositions and mainly aerobic (composting).

If a sufficiently large portion of the manure heap is aerobic then not much methanogenesis will occur and methane emissions will be low. When only parts of the manure store are aerobic this can increase the methane emissions from the anaerobic parts. Composting generates heat and consumes oxygen. This warms the anaerobic parts (probably in the centre). The consumption of oxygen within the heap may also mean that the volume that is anaerobic will grow (Husted, 1994, Sommer and Møller, 2000).

Petersen et al. (1998) report a greater tendency toward composting in swine solid manure than in cattle manure. They report very little heat development (i.e. decomposition activity) in cattle solid manure, but significant temperature increases in swine manure. These observations are consistent with the Swedish study of Forshell (1993) which showed that 27 out of 35 samples from different pig farms showed composting processes but that essentially none of the cattle manures (from 83 dairy farms) showed signs of composting. Only by increasing the straw content could composting in cow manure be initiated.

The implication from the above studies is that quite different emission scenarios may arise for pig and cattle solid manures stored under similar environmental conditions.

Methane from Slurry/Liquid Manure

Here discussion is limited to emission estimates from swine and cattle slurry under cold climate conditions. The intention is to provide some basis for comment on the magnitude of the IPCC default emission factors, which were presented in Table 1. Where possible MCFs are estimated from relevant studies and are collected in Table 6.

The study of Kaharabata et al. (1998) motivates an MCF in the range of 0 to 3%, for cattle and swine slurry, when slurry temperatures are in the range of 2 to 10°C. These are conditions applicable during the Canadian winter and spring which includes periods when the slurry tanks were covered in ice and snow. However, no overall emissions factor for the full seasonal cycle (mean temperature around 10°C) could be deduced from the results presented in that paper.

The laboratory studies of Steed and Hashimoto (1994) indicate an MCF of less than 1% for cattle slurry at 10°C but at 20°C MCFs of around 50% are obtained with variation depending on whether the container is open, closed or inoculated with bacteria.

The paper of Husted (1994) represents one of the few studies that could be found which includes measurements over a full seasonal cycle in a cold climate. It is also one of the few studies found in which there is sufficient information reported to allow MCF values to be calculated without making vast assumptions regarding manure volumes, characteristics etc. Thus for cattle slurry an MCF of 8.1% could be estimated. For swine the estimated MCF is substantially higher at 32%. The measurements were performed in Denmark and the mean temperature during the measurement period was 11.2°C. This is somewhat higher than the mean temperature in southern Sweden of 7.5°C.

Sommer et al. (2001b and 2002a) collected field data from Husted (1994), Khan et al. (1997) and Sommer et al. (2000) and formulated the following rate equation for methane generation from slurry:

$$F(T) = VS_D \text{ x } b_1 \text{ x } \exp(\mathit{ln}A\text{-}E_a/RT) + VS_R \text{ x } b_2 \text{ x } \exp(\mathit{ln}A\text{-}E_a/RT) \qquad \text{eq. (5)}$$

where, F is the emission rate (g CH_4/kg VS/h), A is the Arrhenius parameter, E_a is the activation energy, T the temperature in K. VS_D and VS_R are the readily degradable and the degradation-resistant VS concentrations (g/kg slurry) respectively. The constants b_1 and b_2 are rate correction factors for the degradable and degradation-resistant portions of VS. Sommer et al. assign values of 1 to b_1 and 0.01 to b_2 which shows the large difference in methane generation resulting from VS_D and VS_R respectively. Parameter values for A, *Ea*, b_1 and b_2 have been extracted from field measurements for cattle and swine slurries.

Sommer et al. (2001b) have applied eq. 5 in order to model the annual emissions for typical swine and cattle slurry stores in Denmark. The model includes a balance of the VS composition in the slurry store and accounts for:

- changes in monthly average temperature
- slurry added to the store each month
- slurry removed from the store and applied to fields twice per year
- the decrease in VS content each month due to methane generation.

For a Danish seasonal cycle this gives the following estimates of methane emission from the slurry stores: - for cattle manure 18.1 g CH_4/kg VS, for swine manure 36.7 g CH_4/kg VS. Using the IPCC defaults for B_o for dairy cattle and swine this implies MCF values of 11.2% for cattle manure and 12.2% for swine manure.

The work of Sommer et al. (2001b and 2002a) is considered to be the most significant work for estimating methane emissions from slurry in cold climates. It is based on a fundamental model and supported by several field measurements from different studies. Additionally it takes account of many complexities including the composition of VS and month by month variations in temperature, VS accumulation / depletion in the store.

Since the monthly temperatures in Sweden are lower than those in Denmark one would expect the above MCF values to be somewhat lower. This lends some support to an MCF value of around 10% as suggested in the 1996 IPCC defaults. Although not performed in this study it would be a fairly straightforward exercise to model the operation of a typical Swedish cattle or swine slurry store. This would require some characterisation of the manure (as discussed previously), knowledge of the storage cycle (VS fed to and from the store) and monthly averaged temperatures.

Table 6. Methane conversion factors from slurry systems

Ref:	MCF	Comments
	Cattle	
Husted (1994)	MCF = 8.1%	Danish study, long term measurement, mean temp 11.2°C
Sommer et al.(2001b)	MCF = 11%	conditions as above, based on model which includes storage cycle and Arrhenius relation.
Steed and Hashimoto (1994)	MCF < 0.5%	laboratory tests at 10°C
	MCF ≈ 50%	tests at 20°C
	Swine	
Husted (1994)	MCF = 32 %	long term measurement
Sommer et al. (2001b)	MCF = 12 %	fundamental model

Methane from Solid Manure

The discussion earlier on the complexities of temperature development and oxygen supply would indicate that it is not really reasonable to apply a single, generalised emission factors for methane from solid manures. The emissions are likely to be sensitive to, among other things, straw addition and moisture content. An attempt was made, though, to establish the expected ranges of methane emissions reported for solid manures. Where possible MCFs are estimated from the relevant studies and are collected in Table 7.

Husted (1994) measured emissions from cattle and swine solid manure. The cattle manure was wet, compact and anaerobic from November to April after which it dried, became porous and showed signs of elevated temperature (from composting). This was accompanied by an increase in the emission rate. The overall annual emission translates to an MCF of 2.2%. For pig manure the presence of straw enables partial composting to occur throughout the year which raises temperatures in parts of the heap to above 60°C. The resulting emissions imply an MCF of around 14.2%.

Amon et al. (1998) report the emissions of methane from composted and from anaerobic solid dairy manure. Anaerobic storage during summer gave rise to emissions over twice as high as those for winter storage. Using the reported data with IPCC defaults for B_0 and VS/DM for dairy cattle, an MCF around 5% is estimated. It is uncertain, however, to what extent the storage period used in these tests matches those commonly used in Sweden. Then Amon et al. (2001) report what seems to be the same data. Their data analysis leads to MCF values of 0.41% for actively composted manure, 1.6% for anaerobically stacked farmyard manure in winter and 3.92% for the anaerobic manure in summer. The observation is made by Amon et al. (2001) that the IPCC MCF values are an underestimate in the case of anaerobically stacked farmyard manure.

González-Avalos and Ruiz-Suárez (2001) performed laboratory tests to determine methane emissions factors from dairy and non-dairy cattle in Mexico. The tests were performed at 12°C and reported in terms of kg CH_4/head/yr. Using IPCC default information for VS production from dairy and non-dairy cattle this data may be converted to MCF values. The resulting MCF values are significantly below 1%.

Also from laboratory tests, Steed and Hashimoto (1994) suggest that if the temperature of solid manure is kept low then the MCF is very low (MCF<1% at 10°C). However, the MCF increased sharply if (a) manure containers were kept closed i.e. anaerobic conditions and (b) the temperature increases (e.g. MCF = 65% in a closed container at 30°C).

Table 7. Methane conversion factors for solid manure

Ref:	MCF	Comments
	Cattle	
Husted (1994)	MCF = 2.2 %	Danish conditions, long term measurement, mean temp 22°C
Amon et al.(1998)	MCF = 5 %	anaerobic storage, some data conversion
Amon et al.(2001)	MCF = 1.6 %	anaerobic pile – winter
	MCF = 4 %	summer
Gonzalez Avalos (2001)	MCF < 1 %	laboratory tests
Steed and Hashimoto (1994)		laboratory tests
	10°C MCF = 0	open and closed containers
	30°C MCF = 2%	open container
	30°C MCF = 65 %	closed container
	Swine	
Husted (1994)	MCF = 14.2 %	mean temp 49.2°C

It would appear that the IPCC default MCF of 1% for solid manure is too low when compared to reported field measurements. Laboratory tests, which indicate low MCFs at low temperatures, may be misleading. The difficulties associated with scale in lab tests have been discussed previously. In practice it would seem that cattle manure is predominantly anaerobic, in which case an MCF of at least 2% is motivated. Swine manure which is commonly warmed by partial composting (Forshell, 1993) should have an even higher MCF. Here though support from the literature is thin. Until more measurement data is available for swine solid manure a value of 2%, as for cattle solid manure, is recommended.

Methane from Deep Litter

Monteny et al. (2001) discuss the methane emissions from deep litter housing systems relative to other systems. They suggest that when the deep litter bed remains untreated, anaerobic conditions prevail and considerable methane emissions may result. Studies are cited indicating methane emissions from dairy manure (the enteric component is subtracted) of about 950g CH_4/cow/day. Converting this data using IPCC defaults for VS production results in MCF values of over 100%. This may be due to the effect of the VS content in straw being ignored in the MCF calculation. This raises the question as to how methane emissions resulting from straw decomposition should be accounted for? No other studies could be found which could be used for estimating MCFs for deep litter systems.

Sommer (2001), Sommer and Møller (2000) and Sommer and Dahl (1999) discuss carbon balances and methane emissions from deep litter. These are all from the second phase of storage associated with deep litter i.e. storage or composting after removal from the animal stalls. Methane emissions appear to be sensitive to the amount of straw present and the density of the deep litter. Without information regarding the VS content derived from straw or how this affects the B_0 value, it is difficult to estimate effective methane conversion factors for deep litter.

The lack of literature and the uncertainty associated with the methane emissions from the deep litter (both inside and outside of the animal houses) mean that no MCF can be suggested here. Because deep litter is less sensitive to the outdoor temperatures, Swedish conditions no longer present a ‘special case’ with respect to climatic effects. The currently valid IPCC default MCF for deep litter is 39%. Intuitively, seems high, but may possibly be motivated if straw decomposition is significant.

Nitrous Oxide Emission Factors

Parameters which Influence Emissions

Effects of temperature

Nitrous oxide is produced by nitrification and denitrification. The rate of both these processes increases with increasing temperature (Granli and Bøckman, 1994). Granli and Bøckman also cite studies indicating that denitrification proceeds at temperatures as low as –4°C but that temperatures above 5°C are required for the rates to be significant. A seasonal dependence is seen in N_2O emissions from soils, with the majority of emission occurring during warmer months. This would tend to support the possibility that emission rates from manures with cold storage conditions, as found in Sweden, may give rise to lower N_2O emissions than under warmer climatic conditions.

However, Sommer et al. (2000) report that no relationship was found between N_2O emissions and the temperature of air or the manure slurries tested. They cite Willers et al. (1993) who make a similar observation. The only climatic effects found by Sommer et al., to be significant was precipitation and its effect on the wetting of the surface crusts (discussed next).

In solid manures however, temperature effects on N_2O emissions may be observed. When composting occurs and high temperatures are generated, low N_2O emissions are measured (Sommer, 2001). This is probably since nitrifying and denitrifying bacteria are not generally thermophilic (Hellmann et al., 1997). In the composting of deep litter, Møller et al. (2000) also report an increased N_2O after the cooling of composting litter has occurred.

Effects of slurry surface cover

While surface covers on slurries may reduce methane emissions they appear to have the opposite effect on nitrous oxide emission. Sommer et al. (2000) found that nitrous oxide emissions were near zero when no surface crust was formed or when the surface crust was saturated. However, in the summer when the surface crust was at least partially dried and porous, N_2O emissions increased significantly. It is suggested that the surface layers and straw provide a mosaic of aerobic and anaerobic sites, which favours nitrous oxide generation.

Clemens et al. (2001) cite studies of Kuisl, (1999) and Hüther (1999) which respectively indicate that uncovered slurry may actually act as a slight sink for N_2O, while straw covers result in increased N_2O emissions. Since surface covers have benefits for ammonia and methane emissions, Clemens et al. suggest that ’foil’ type covers be used.

Other influences

Straw addition – as discussed with respect to methane emissions, the straw content in solid manure affects the air supply to the manure and thus the composting behaviour and temperature development. These factors in turn have an effect on the nitrification and denitrification processes. As for solid manure discussed above, nitrous oxide from deep litter is reported to increase as O_2 concentration decreases (Groenestein and van Faassen, 1996).

Nitrous Oxide from Slurry/Liquid Manure

Nitrous oxide emissions from slurry systems are often assumed to be zero as a result of the anaerobic conditions (e.g. Monteny et al., 2001). Jungbluth et al. (2001) cite results from Amon et al. (1999) which, when recalculated using IPCC defaults for N_{ex}, suggest an emissions factor of 0.14%.

Sommer et al. (2000) report no nitrous oxide emissions from cattle slurry stores which had saturated slurry covers (wetted as a result of a positive water balance). However, during the summer when the covers were drier, N_2O emissions of up to 25 mg N/m2/hr were recorded. The explanation for this was discussed above with respect to the effect of surface covers. The highest N_2O emissions resulted from surface crusts. Converting the results of Sommer et al. (2000) indicates EF values ranging from near zero to 2.3% at the peak emission. An average value for the EF for a slurry with a natural crust would appear to be around 0.5%.

The nitrogen balances of Petersen et al. (1996) indicate the losses of nitrogen as nitrous oxide from slurries were virtually negligible.

Phillips et al. (1997) report that the nitrous oxide emissions from a weeping wall cattle manure store were insignificant. The explanation offered was the truly anaerobic conditions. The manure in that study had a dry matter content of 16%. According to the current Swedish classification this would be a semi-solid manure and thus have the higher N_2O emission factor (2%). However, the IPCC border of 20% between solid and liquid system means that this should have the lower emission factor of 0.1%. Thus the results of Phillips et al. would tend to agree with the use of the low emissions factor for anaerobic manure.

Table 8. Emission Factors for Nitrous Oxide from Slurry Manure

Ref:	EF	Comments
Jungluth et al. (2001) citing Amon et al., 1999	EF = 0.14%	Austrian study, unspecified storage conditions
Petersen et al. (1996)	EF << 1%	Danish study
Sommer et al. (2000)	EF ≈ 0.5%	increased N_2O emissions due to natural surface crust

The low EF value of 0.1% supplied by the IPCC for slurries appears reasonable and is consistent with reports of low emissions in the literature. However, the effect of surface covers, reported by Sommer et al. (2000) could imply that this value is too low, particularly where natural crust covers are used. Since these covers are dominant in Sweden, further study of this emission factor would be motivated. Until local measurements can be performed, or until more studies are published reporting higher emissions factors, the IPCC default of 0.1% should be used.

Nitrous Oxide from Solid Manure

The limited access to oxygen in stored solid manure means that nitrous oxide emissions are more significant than those from slurry, where most of the material is under truly anaerobic conditions.

Amon et al. (2001) report lower nitrous oxide losses from composing cattle manure than from anaerobic piles (EF between 0.3% and 0.8%) . This is reportedly consistent with the findings of Hüther (1999) who found increasing N_2O emissions as oxygen supply decreased (EF between 0.3% and 1.5%). The explanation offered is that most of the N_2O is produced by denitrification, which is favoured by the low oxygen supply.

For pig manure, Petersen et al. (1998) measured nitrous oxide emissions to be between 0.5% and 2% of the denitrification losses. This translates to, at most, an emissions factor of 0.5% of the total N. However, an earlier report from Petersen et al. (1996) for swine manure indicated a maximum loss of nitrogen, as N_2O, of 2% of the total nitrogen in the manure.

Table 9. Emission Factors for Nitrous Oxide from Solid Manure

Ref:	EF	Comments
Amon et al. (1997)	EF = 0.4%	cattle manure
Amon et al. (2001)	summer EF < 1% winter EF = 1%	anaerobic storage, cattle manure
Hüther (1999) cited by Amon et al. (2001)	EF = 0.3-1.5%	cattle manure
Petersen et al. (1996, 1998)	EF = 0.5 – 2 %	swine manure

The studies reviewed tend to indicate an emissions factor of 2% or lower. Thus the IPCC default of 2% is at the higher end of these estimates but appears to be reasonable.

Nitrous Oxide from Deep Litter

The mixing of straw with manure can reportedly lead to an increase in nitrous oxide emissions by about 8 to 10 times (Ross et al., 1999 cited by Jungbluth et al., 2001). The study of Ross et al. was for swine manure. Since the results are quoted on a basis of area it is not possible to calculate EF values from them. However, the results would tend to indicate that the nitrous oxide emissions from deep litter should be higher than from solid manure storage. This is supported by Groenestein and van Faassen (1996) and Monteny et al. (2001) suggesting emissions factors around 15 to 21% for manure from fattening pigs. These high levels are, however, from tests where there was active mixing of the deep litter mats. Monteny et al. discuss the effect of management of the straw bed and indicate that if the bed stays untreated, it becomes compacted and anaerobic and virtually no N_2O is expected.

Møller et al. (2000), studied the effects of different straw/manure ratios in swine deep litter during production. At low straw addition ratios (0.67kg/kg weight gain of the pigs) low temperatures were recorded in the litter. At greater than 1.2 kg straw the temperature increased up to between 40 and 70°C. Nitrous oxide concentrations were reportedly low for the dense, anaerobic mat with low straw addition. The higher straw ratios gave rise to different time profiles of N_2O release. However, no quantitative estimates of the overall N_2O loss were made.

Thelosen et al. (1993 cited by Møller et al., 2000) estimated N_2O emissions of 5% of the excreted N. This was for a deep litter mat of sawdust, which was mixed once a week. The mixing was thought to enhance the denitrification. When the deep litter mats are not mixed, Møller et al. (2000) indicate nitrous oxide emissions significantly lower than those of Thelosen et al. No estimate of the percentage of nitrogen lost as N_2O is given though.

Sommer (2001) investigated the greenhouse gas emissions from cattle deep litter manure. The deep litter was subjected to a variety of treatments including compacting of the deep litter or a reference (untreated). The N_2O emission factors for the compacted and untreated litter (after 124 days of storage) are 0.3% and 0.1% respectively. It should be noted that in this study the emissions measurements started after the deep litter had been removed from the animal house and thus does not represent the full emission from ’deep litter manure management’. Sommer and Dahl (1999) also study emissions from deep litter after removal from the animal houses. The nitrous oxide losses represent at most 0.0005% of the total nitrogen in the litter. Sommer and Møller (2000) reported N_2O -N emissions of 0.8 % of the total nitrogen from compacted swine deep litter beds and 0.1% from lower density beds. Measurements took place during 4 months of storage/composting after the end of the fattening period.

Table 10. Emission Factors for Nitrous Oxide from Deep Litter Manure

Monteny (2001) citing Groenestein et al. (1993 and 1996)	EF = 15-21 %	Swine deep litter with periodic mixing and treatment of material
Møller et al. (2000) cite Thelosen (1993)	EF = 5%	Active mixing of mat
Sommer and Møller (2000)	EF = 0.1-0.8%	‘used’ deep litter
Sommer (2001)	EF = 0.1-0.3 %	used cattle deep - either compacted or untreated

In Sweden, active mixing of deep litter mats is not common. Thus an EF ‘significantly below 5%’ would be indicated by the study of Møller et al. (2000). Differences between cattle and swine litter could be substantial due to the differences in straw addition and bed density. The storage of deep litter after ‘use’ in the animal houses seems to be responsible for relatively little nitrous oxide emission. Based on the literature reviewed, there is not much support for any deviation from the IPCC recommended EF of 2%.

Conclusions and Recommendations

Conclusions from this review are offered in brief format below. These are followed by a summary of the recommended emissions factors and suggestions for future work whose aim is to address the most critical gaps in current knowledge.

There is, in general, very little published data from measurements of methane and nitrous oxide emission from manure management. A limited number of these contain data of sufficient quality and duration that can be used to estimate emission factors. This gives a weak basis for either supporting or suggesting improvements of the IPCC default emission factors.

Methane emissions

The IPCC default values for the volatile solids, VS, content of cattle and swine manure seems to be an overestimate. Measurements on Swedish cattle and swine manures indicate that a value of 87% VS/DM for all cattle and swine categories would be more reasonable than the IPCC defaults.

The composition of the VS is affected by diet and other factors and is thus of primary importance to the methane generation. These effects may be seen in the 'spread' of methane generation potentials, B_0, reported in the literature. In the absence of measurements from fresh manure, taken from typical Swedish farming operations, there is no basis for deviation from the IPCC default values.

For slurry systems, there seems to be reasonable evidence that an MCF of 10% is more appropriate in Sweden than the IPCC, 2000 default of 39%. No basis for the 39% value could be found.

For both cattle and pig solid manure, an MCF of 2% is argued as being more likely than the IPCC default of 1%. For solid wastes though, it seems unreasonable to apply a single MCF to all manure categories. Due to differences in straw contents and resulting aerobic conditions and temperature development it may be necessary to at least differentiate between cattle and swine solid manure. For swine solid manure, a much higher MCF value (than the recommended 2%) is probably motivated but further study is required before a higher quantitative estimate can be implemented.

Deep litter systems have been added as a category for methane and nitrous oxide emissions (IPCC, 2000). The IPCC default MCF is 39%. However, no support or contradiction can be found for this value.

Nitrous oxide emissions

The literature reviewed indicates a range of emission factors for nitrous oxide which is in fair agreement with the IPCC default values of 2% for solid and deep litter systems and 0.1% for slurry systems. For slurry systems covered with a natural crust higher N_2O emissions could result. Since these types of covers are widespread in Sweden local measurements should be carried out to determine a more suitable emissions factor.

Manure management systems

In Sweden the dominant AWMS categories are solid and slurry systems which, together, account for over 90% of the total manure produced.

The Swedish inventory has, in the past, classified ‘semi-solid’ manure as ‘solid’ for estimating methane and nitrous oxide emissions. But for nitrous oxide emissions estimates, the IPCC suggest that the border between ‘solid’ and ‘slurry/liquid’ systems is 20% DM. This means that ‘semi-solid manure’ in Sweden should be classified as ‘slurry/liquid’, at least for nitrous oxide emissions.

No similar solid-liquid division criteria could be found in the IPCC documents for methane emissions. However, the value of 20% is probably based on the transition between the dominance of anaerobic or aerobic conditions. This would imply that a similar classification criterion could be applied with respect to methane emissions.

The Swedish statistics for ‘semi-solid’ manure are uncertain. It is suspected that many systems currently classified as ‘solid’ are in fact ‘semi-solid’ systems and thus, according to the IPCC, equivalent to ‘slurry/liquid’ slurry. In view of these considerations, the ‘semi-solid’ category could now have significant impact on the overall, manure management inventory.

Recommendations

Based on the findings in this review and the conclusions listed above, recommended emission factors are summarised in the table below.

Recommended methane conversion factors (MCF) and nitrous oxide emission factors (EF_{nit}) for Swedish conditions

System	Factor	Recommended value	IPCC default	Motivation
Slurry / liquid	MCF	10 %	39 %	supported by model and literature
	EF_{nit}	0.1 %	0.1 %	agreement with literature
Solid	MCF	2 %	1 %	should probably be even higher for swine
	EF_{nit}	2 %	2 %	agreement with literature
Deep litter	MCF	39 %	39 %	no basis for deviation from IPCC
	EF_{nit}	2 %	2 %	weak support from literature no basis for deviation from IPCC

In order to address the most critical uncertainties further research is required. The recommended activities listed below are considered likely to have the most significant impact on the accuracy of the overall emissions estimate.

Manure characterisation – fresh manure samples, representative of both swine and cattle categories should be characterised in terms of methane generation potential, B_0, total VS content and VS composition (in order to determine degradable VS content).

Classification of AWMS – the distribution of waste management systems between the IPCC categories of ‘solid’ and ‘liquid/slurry’ has been identified in this review as a source of uncertainty. The so-called ‘solid’ systems in Sweden need to be resolved in terms of the IPCC definition of a DM content over 20%. This exercise should be accompanied by an investigation of the relevance of the value of 20% DM as the criterion for division between different emission regimes.

Methane from solid manure – field measurements of methane emission from cattle and swine solid manure are required in order to obtain better MCF estimates. The tentatively recommended values are not well supported by the literature.

Nitrous oxide from covered slurry – the findings of Sommer et al. (2000) indicate that N_2O emissions from covered slurries with natural crusts could be substantially higher than indicated by the IPCC default factors. Since this is a major manure management category in Sweden, field measurements of N_2O emissions from covered slurry tanks need to be conducted.

Methane from slurry – the model of Sommer et al. (2001b and 2002a) represents a sound basis for estimating the effective MCF from slurries. This model should be checked and if necessary calibrated for application under Swedish conditions.

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