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**Non-CO<sub>2</sub> greenhouse gas emissions associated  
with food production:  
methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O)**

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## **Abstract**

It is well known that the agriculture and livestock sectors are large contributors of N<sub>2</sub>O and CH<sub>4</sub> emissions in countries with agricultural activities and that remedial measures are needed in these sectors in order to curb contributions to global warming. This study examines non-CO<sub>2</sub> greenhouse gas emissions associated with the production of food. Methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are the most relevant greenhouse gases in this category, and they are emitted mainly in the agricultural sector. These greenhouse gases have a Global Warming Potential much higher than CO<sub>2</sub> itself (25- and 298-fold higher, respectively, in a 100-year perspective). Emission intensities and the corresponding uncertainties were calculated based on the latest procedures and data published by the Intergovernmental Panel on Climate Change and used to facilitate calculations comparing greenhouse gas emissions for food products and diets. When the proposed emission intensities were applied to agricultural production, the results showed products of animal origin and the cultivation of rice under water to have high emissions compared with products of vegetable origin cultivated on upland soils, such as wheat and beans. In animal production the main source of greenhouse gas emissions was methane from enteric fermentation, while emissions of nitrous oxides from fertilisers were the main sources of greenhouse gas emissions for cereal and legume cultivation. For rice cultivation, methane emissions from flooded rice fields contributed most. Other significant sources of greenhouse gas emissions during animal production were manure storage and management. We suggest that the proposed emission factors, together with the associated uncertainties, can be a tool for better understanding the potential to mitigate emissions of greenhouse gases through changes in the diet.

## **Keywords**

Climate change—N<sub>2</sub>O — CH<sub>4</sub> — Agriculture and livestock production

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## Greenhouse gas emissions in the agriculture sector

Anthropogenic emissions of greenhouse gases (GHG) arise from a large variety of activities. At present, and after several decades of work, the Intergovernmental Panel for Climate Change has compiled a substantial body of evidence and assessment of the anthropogenic and natural causes of climate change ([www.ipcc.ch](http://www.ipcc.ch)). Working Group I recently released its latest report on the Physical Basis (IPCC-WGI, 2007), with details of the reviewed findings about the chemical and physical processes affecting climate. During the same time an expert panel has published an updated version of the Guidelines for National Greenhouse Gas Inventories, in which individual production and consumption activities are assessed (IPCC, 2006) (released 2006 and with additions in 2007). The main sectors dealt with in these Guidelines are: energy; industrial processes and product use (IPPU); agriculture, forestry and other land use (AFOLU); and waste.

Energy production and use is the leading sector in emissions according to IPCC-WGI (2007), and CO<sub>2</sub> is the particular greenhouse gas with the largest relevance. However, other gases, so called non-CO<sub>2</sub> gases, are also important. For instance methane (CH<sub>4</sub>), as a contributor to climate change, is second only to CO<sub>2</sub>, and nitrous oxide (N<sub>2</sub>O) is third in total emissions affecting the climate. The global increases in methane and nitrous oxide in the atmosphere are primarily due to agriculture. The magnitude of emissions depends on the production techniques used.

An assessment of non-CO<sub>2</sub> greenhouse gases is relevant for designing sustainability strategies because they will be present even if a reduction in fossil fuel emissions occurs, whether through efficiency improvements or from the increased use of renewable energy sources.

In this report, we study emissions of non-CO<sub>2</sub> greenhouse gases related to the agricultural sector based mainly upon IPCC recommendations in the National Greenhouse Gas inventories. The aim was to build a database of default emission factors that can be used to analyse foods and diets in relation to their impact on the energy balance of the climate system. Due to the wide variety of food products with different regions of origin available at the global food market, we chose the *Tier 1* methodology for all estimations (IPCC, 2006), and evaluated the uncertainties for each case. The *Tier 1* method is a simplified method using default values relevant for large regions of the globe, and representing standard production practices.

We present default emission factors that can be used when food is studied from a life cycle perspective when the agriculture phase is included. The emission factors can be used for example to estimate emissions from the feed production needed to produce a certain amount of meat, or to estimate emissions during rearing of animals or cultivation of crops subsequently used for human consumption. In such studies, estimates of CO<sub>2</sub> emissions from fossil fuels are usually also included. However, we do not present emission factors from the use of fossil fuels in agriculture in this report. Depending on the food analysed, these can

include fuel use during fertiliser production, growing and drying of crops, food processing, transportation, storage, cooking and waste treatment. The amounts of product analysed with respect to the crop harvested must then be considered. Default emission factors for CO<sub>2</sub> will be published in a forthcoming work. A model for estimating energy use for irrigation has already been developed (González and Carlsson-Kanyama, 2005).

Emissions relevant to the agricultural sector described in this report are CH<sub>4</sub> and N<sub>2</sub>O. Both CH<sub>4</sub> and N<sub>2</sub>O emissions mainly arise from livestock production and cultivation practices under flooded conditions. Manure management is a leading cause of N<sub>2</sub>O emissions, while CH<sub>4</sub> is largely produced in the digestive system of ruminants and from their manure and in flooded rice fields.

Previous studies have shown that choice of food and diet can influence the energy requirements for the provision of human nutrition and the associated GHG emissions. Meals similar in caloric content may differ by a factor of 2-9 in GHG emissions (Carlsson-Kanyama, 1998; Engström et al., 2007). An analysis of the energy inputs required to produce a large number of food items allowed meals with similar nutritional value to be compared and a difference up to a factor of four was found depending on the items chosen (Carlsson-Kanyama et al., 2003). All these studies identify certain foods as more resource demanding/polluting than others, including animal products and certain vegetable products produced in resource-intensive ways.

Present trends in food choices point towards increased environmental impacts (Carlsson-Kanyama and Linden, 2001; Carlsson-Kanyama, 2004) and future more environmentally friendly diets need to be identified. The matter was discussed by Duchin (2005) from the multiple viewpoints of health, sustainability and environment. This author studied a Mediterranean diet, consisting mainly of plant-origin foods but not excluding a small proportion of meat and other animal products, and found that this diet is closer to public health recommendations and has a lower environmental impact than the current average US diet.

Recently, Hawkes (2006) investigated the correlation between agricultural policies and cardiovascular health in Latin America and found that production and consumption of food items with negative influences on public health have increased. Meanwhile, the production of fruits and horticultural products, positively associated with cardiovascular health, has also increased but most of it is exported and not consumed in Latin America. According to the 2003 Joint Expert Panel of the World Health Organization and the Food and Agriculture Organization (WHO-FAO, 2003), 40% of non-communicable chronic diseases might be prevented by healthier food choices. The Panel recommends a diet with a lot of foods of plant origin, whole grains, little or no saturated fats, no trans-fats (such as those found in hydrogenated oils), no fried foods, and a limited use of meats and whole-fat dairy products (if included at all).

Thus, there seems to be convergence between what would reduce environmental impacts and what would improve public health, particularly non-communicable chronic diseases. This

convergence is a solid foundation for investigating policies on possible changes in diet. A quantitative assessment may be the first step to analyse pathways and potentials for improvement.

## Global Warming Potential

There exists a diversity of gases in the atmosphere, produced either naturally or by humans, with the capacity to enhance global warming. The individual strength of such gases is quantitatively assessed using the concept of radiative forcing (RF). The unit of measurement of RF is  $W/m^2$ , and its definition relates to the change in net (incoming and outgoing) solar and long-wave irradiation under certain troposphere and surface temperatures. Each GHG has a Greenhouse Warming Potential (GWP), which is calculated by the time-integrated RF of 1 kg of a certain gas compound relative to that of 1 kg of the reference gas  $CO_2$ . By definition, the GWP of  $CO_2$  equals 1, and therefore the GWP for non- $CO_2$  gases is given in units of  $CO_2$ -equivalents by a common unit of weight (for example, kg  $CO_2$ -equivalents per kg  $N_2O$ ). Agriculture and food production is a sector with a diversity of emitted gases, namely: methane ( $CH_4$ ), nitric oxide ( $N_2O$ ), hydrofluorocarbons (HFCs), sulphur hexafluoride ( $SF_6$ ), in addition to  $CO_2$ . These gases are collectively called long-lived greenhouse gases (LLGHGs).

Since LLGHGs emitted into the atmosphere interact with other gases, aerosols and radiation, a decay or enhancement of their concentration and activity is expected. Therefore, when evaluating the GWP of different gases, a time period is used to address average values relative to  $CO_2$ . Table I summarises different options relevant for gases emitted from agriculture and food production.

*Table I: Global Warming Potential (GWP) for different gases relevant for agriculture over three different time perspectives. Factors are given in  $CO_2$ -equivalents, taken from Table 2.14 in WG1-IPCC (2007).*

GHG	20-year	100-year	500-year
$N_2O$	289	298	153
$CH_4$	72	25	7.6
HFC-23	12000	14800	12200
HFC-134a	3830	1430	435

For example, a GWP of 25 for  $CH_4$  in a 100-year perspective means that all amounts obtained in grams of  $CH_4$  in the inventories should be multiplied by 25 to convert them into kg  $CO_2$ -equivalents.

For instance, HFCs are a new generation of gases that replace the previous ozone-depleting chlorofluorocarbons (CFCs). They are used for refrigeration, and small amounts leak from the refrigerators and freezers during operation and maintenance. Even though the amounts released are small in terms of grams, the GWP of HFCs ranges from 124 to 14800. Table I shows the GWP for the two types of HFC gases with the largest concentration in the

atmosphere (taken from Table 2.1 in WG1-IPCC, 2007). In India, for example, the contribution of HFCs to the total national inventory of CO<sub>2</sub> equivalents is less than 1%, while the agricultural sector is reported to contribute 28% of the total emissions when all greenhouse gases are included (Garg et al., 2006). It is interesting to include emissions of HFCs when analysing food items, as fresh food is commonly stored in a refrigerated environment. Other LLGHGs might have even higher GWPs than HFCs. An example is SF<sub>6</sub>, which has a GWP of around 23000. This gas is used extensively in the electrical insulation of high voltage transformers and breakers.

The values in Table I are the latest published by the IPCC-WGI, and are based on models and experiments. Previous data from 1996 and 2001 differed slightly from the new values for N<sub>2</sub>O (310 against 298 for a 100-year span); However, the value for methane has been changed from 21 in 1996 to 23 in 2001, and rose to 25 at the latest estimate (IPCC, 2007). The reason is that more accurate data have been obtained, and so the RF estimate has been significantly increased, particularly due to the increase in water vapour in the stratosphere.

## Nitrous oxide (N<sub>2</sub>O)

The aerobic microbial oxidation of ammonia to nitrate is called nitrification, while denitrification is the reduction of nitrate to gaseous nitrogen (N<sub>2</sub>). Both reactions produce the intermediate gaseous nitrous oxide (N<sub>2</sub>O) through microbial activities in the soil and eventually this gas is released to the atmosphere. These processes are more relevant when nitrogen (N) is added to soils, and therefore should be accounted for in anthropogenic N additions to agricultural soils.

On the other hand, in animal production, the storage and handling of manure also contribute to N<sub>2</sub>O emissions. The rate of nitrification in stored manure depends on the amount of N and the available oxygen necessary for the chemical reaction. Thus, nitrification does not occur in anaerobic processes but in denitrification of manure, nitrites and nitrates lead to N<sub>2</sub>O emissions even for anaerobic conditions. A consequence of these reactions is that the emission factors for manure storage and management have to be evaluated for each particular procedure in livestock production.

Here, four major direct contributors are considered:

- a) N<sub>2</sub>O from application of artificial fertilisers on soils
- b) N<sub>2</sub>O from application of manure on soils
- c) N<sub>2</sub>O from crop residues applied on soils, including N-fixing crops
- d) N<sub>2</sub>O associated with storage and handling of manure (AWMS, Animal Waste Management Systems)

Emission factors and activity data for the first three are given in Chapter 11, Volume 4 of the 2006 Guidelines for Greenhouse Gas Inventories (IPCC, 2006), and the last one in Chapter 10.

## Methane (CH<sub>4</sub>)

Methane is an end product of the degradation of organic matter under anaerobic conditions. In herbivores, and more intensively in ruminants, cellulose and other complex carbohydrates are digested with the aid of micro-organisms, and the associated processes are collectively called enteric fermentation. Methane is produced in this type of microbial digestion, with the amount released depending on animal type, quality and quantity of feed, and characteristics of livestock. The main ruminants producing extensive amounts of CH<sub>4</sub> are cattle, buffalo, sheep, goats and deer, though only animals under domesticated conditions are considered here. Methane is produced by the fermentation of feed within the digestive tract, and can be released either by mouth or faeces. The more feed intake, the higher the CH<sub>4</sub> emissions, and so intensive management give rise to higher per-head emissions. However, in intensive systems, the production of e.g. meat or milk may be higher and therefore the emissions per unit of food obtained could be lower than with less intensive agricultural practices.

Manure storage in anaerobic conditions can also produce methane emissions. In this case the decomposition of the manure is the relevant mechanism, and thus here it is accounted for independently from enteric fermentation. Higher emissions are found when animals are kept in large numbers in confined conditions, such as dairy farms, cattle feedlots and intensive pig farms, where manure is usually handled in liquid systems. The decomposition of manure (both urine and faeces) in liquid form can produce a significant amount of methane. Manure handled as a solid or excreted directly onto pasture decomposes mainly in an aerobic fashion and produces less CH<sub>4</sub>. For instance, the IPCC gives a default value of methane emitted from poultry manure stored in a solid dry form equal to 0.03 kg CH<sub>4</sub> per animal and year, but the emission factor rises to 1.4 kg CH<sub>4</sub> per animal and year if the poultry manure is handled wet (Table 10.15 of IPCC, 2006).

Other sources of methane in agriculture are crops under permanent or temporary flooded conditions, such as rice. In these cases, the micro-organisms in soil under water produce methane, and different parts of the plant emerging through the surface of water can improve gas transport to the atmosphere. A similar mechanism occurs in hydroelectric dams. Rice produced in dry conditions (usually called upland rice) does not lead to significant emissions of CH<sub>4</sub>, except for those derived eventually from the use of manure as fertiliser.

To account for CH<sub>4</sub> emissions in food production we deal with three cases:

- e) CH<sub>4</sub> from manure management
- f) CH<sub>4</sub> from enteric fermentation
- g) CH<sub>4</sub> from flooded rice cultivation

The importance of non-CO<sub>2</sub> emissions in total national greenhouse gas inventories depends on regional and country characteristics. There is a global tendency for increasing animal production, either for local consumption or for exports (Smil, 2002) and the amounts of NO<sub>2</sub> and CH<sub>4</sub> emanating from these activities are expected to rise. In Sweden, 20% of the total

greenhouse gas emissions come from CH<sub>4</sub> and N<sub>2</sub>O, mainly originating from agriculture (Swedish Environmental Protection Agency, 2007). In the US, the only categories with similar methane emissions to agriculture are landfilling and gas mining. Global estimates from the US Environmental Protection Agency show that more than 80% of N<sub>2</sub>O and 50% of CH<sub>4</sub> emissions arise from the agriculture sector (EPA, 2006).

## Methodology and boundary conditions

IPCC (2006) suggests different approaches to calculate emissions. These approaches are called *Tier 1*, *Tier 2* and *Tier 3*, with increasing levels of detail and complexity. *Tier 1* is suitable for cases in which either no detailed data are available or global results are sought, though significant variations such as climate, region, type of harvest and animal rearing, irrigation procedure, soil and manure management are considered. In this approach, agronomy data from global databases can be used (for instance FAO data). *Tier 2* and *3* are recommended for key categories that are most relevant for the country or region. In *Tier 2*, similar equations as in *Tier 1* are used, but more specific data on animal feed quality (digestibility), amount eaten per animal and year, or local use of fertilisers and manure, are required. The *Tier 3* procedure requires extensive studies and specific data to obtain local emission factors with low uncertainty. Clearly, *Tier 2* and *3* methods would have fewer uncertainties, but they call for detailed information that might not always be available. Then, IPCC (2006) suggests that combined methods could be used, i.e. part of the inventory can be analysed on one or more *Tier*.

For the purpose of the present study we chose the *Tier 1* approach for all quantitative estimates. This choice allowed us to make calculations with more global validity and to include food products from different countries and regions. Basic emission factors and activity data from IPCC (2006) were used throughout. In the case of cereal or animal products from specific countries, yields and fertiliser data were taken from FAO, National Statistics Sweden (SCB) and National Institute for Agronomy (INTA) of Argentina.

Again we point out that for a complete analysis of food items, direct and indirect greenhouse gas emissions, CO<sub>2</sub> emissions associated with the production chain, transport, provision of feed, machinery, etc. should also be included. These are not part of the present study and will be dealt with in a forthcoming work.

## Uncertainties

In the literature, the term uncertainty is used in a wide sense, including statistical variance as well as deviations originating from discrepancies in assessing the best known figures (Rypdal and Winiwarter, 2001). The first type (variance) is expressed as a random error which influences the mean values in either direction; the second, however, might carry a systematic component that could also affect mean values with biased quantities. Accuracy and precision are different concepts. Accuracy relates to best assessment of a mean value,

which is considered accurate if bias or systematic errors are at a minimum. Precision relates to the random uncertainty caused by statistical variance in data about mean values.

Systematic (or bias) uncertainties relate to the way each contribution is accounted for, and they can be thought as of conceptualisation origin, i.e. failure to include a concept or partial data. For example, a recent study by Johnson and Johnson (2006) shows a large variability in estimates of US inventories for agriculture when the indirect emissions are taken into account in animal production. These authors found that if N<sub>2</sub>O and CO<sub>2</sub> imbedded in the feed of animals and the run of their facilities were included, the agricultural inventory could be expected to increase the total by 38%, with the animal production sub-sector being 56% of the total for agriculture. Johnson and Johnson (2006) also stressed the importance of another source of indirect uncertainties arising from conceptualisation. They consider that the assumptions about digestibility of feed used in the US inventory are too high, thus leading to CH<sub>4</sub> emission levels that are too low. Data from the National Academy, although available, were not used when reporting to the UN.

In another example, uncertainties in GHG inventories for Finland are discussed in Monni et al. (2006). Agriculture is one of the sectors with the most uncertainties in emission estimations, accounting for over 20% of the total uncertainty in inventories for Finland (Monni et al., 2006). A combination of natural variability of agricultural relevant parameters, plus a lack of scientific precise data on specific emission factors and the overall variability in production techniques, makes agriculture a sector relevant for more detailed studies.

In the present work, the uncertainties in emissions are derived directly by a combination of individual uncertainties, which are given by IPCC (2006) for every variable. In order to combine uncertainties, two procedures suggested by IPCC can be used: *Approach 1* combining uncertainties for multiplications and additions; or *Approach 2* using a more elaborate Monte Carlo simulation. The calculation of emissions in *Tier 1* is achieved as a multiplication and addition of different variables, most of them independent and carrying a range of uncertainty depending on how well the individual variable can be known (IPCC, 2006). For the present work we chose *Approach 1* for combining uncertainties (the equations used for combining uncertainties are shown in the Appendix). When the uncertainties are very large, and so *Approach 1* might not be valid, the resulting uncertainty gives still an indication and can be corrected by empirical equations (IPCC, 2006).

In some cases emission factors have large uncertainties, reaching 100% or 200%. By definition, emissions factors cannot be lower than 0, so an uncertainty larger than 100% would lead to negative numbers with no meaning. Then, when large uncertainties occur it is practical to define the uncertainty as a factor that affects the mean value in either way, adding or subtracting. For example, the emission factor for N<sub>2</sub>O emission from N applied on fields is 0.01 kg N<sub>2</sub>O-N / kg N, with an uncertainty factor of 3. Therefore the emission range is 0.003 to 0.03, with the mean value being 0.01. In another example, the default emission factor for manure management in dry lots has a mean value of 0.02 and an uncertainty of a factor of 2, meaning that a range from a minimum of 0.01 to a maximum of 0.04 determines

the interval of confidence (IPCC, 2006). These are examples of quantities with large asymmetrical uncertainties.

In other cases, uncertainties have meaning only in one direction, whether plus or minus. This occurs with emissions factors lacking enough data for a more accurate estimate, and so valued as the maximum amount. For instance, when CO<sub>2</sub> emissions from urea application are included in inventories, the emission factor is directly the molecular weight percentage of carbon in urea, which is 0.2. The assessment of expert panels is that the uncertainty for this quantity is -50%, and so the range of values for emission of CO<sub>2</sub> from urea application is 0.1 to 0.2, with the maximum as the most probable value.

## **Emission intensities**

The following equations give combined emission factors relevant for food analysis. The results are given in mass of CO<sub>2</sub>-equivalent for a given mass of product at a certain stage in the production chain. In this way, emission factors developed in a similar manner for other parts of the production chain can be combined in order to perform a complete analysis after establishing the mass flows in the system.

The specific default emission factors from IPCC can be combined with other variables representing the food items studied. Then, combined default emission factors including information on particular production techniques or regions can be calculated. For example, IPCC gives default emission factors for CH<sub>4</sub> emission per m<sup>2</sup> of rice field. These values can be combined with data from FAO (2004b) on rice production and flood regimes, and generate combined default emission factors for CH<sub>4</sub> emissions per kg of rice.

In this report, we study emissions related to the agriculture sector, with the goal of applying them to assess environmental impacts of food production and consumption. Direct and indirect non-CO<sub>2</sub> emissions are a key category in this sector, while CO<sub>2</sub> emissions during food production correspond mainly to the energy use involved in food processing.

The present report studies emission factors and uncertainties for processes related to animal and crop production. The aim was to build a database of default emission factors that can be used to analyse foods and diets, in Sweden and abroad. Due to the wide variety of products and regions of origin, we chose the *Tier 1* method for all estimations, and evaluated the uncertainties for each case. The present work differs from a national inventory in that we calculated emissions per unit of product produced. As mentioned previously, the mass flows in the production chain have to be known if such emission factors are to be used correctly.

### **a) Nitrous oxide (N<sub>2</sub>O) from synthetic fertilisers applied on soils**

The application of fertiliser increases the probability of N<sub>2</sub>O being emitted from microbial activity in soils. However, a fraction of direct volatilisation as ammonia and nitrogen oxides has to be subtracted because this is not used by the microbes in the soil. Then, the amount of N<sub>2</sub>O emitted from application of artificial fertilisers is:

$$N_2O_{fertil} = M_{fertil} * (1 - fr_{atm,f}) * \varepsilon_{factor} * (M_{N_2O} / M_{N_2}) * GWP_{N_2O} \quad (1)$$

where

$M_{fertil}$  = mass of nitrogen in fertiliser needed to produce the amount of product analysed (kg N applied per kg product analysed )

$fr_{atm,f}$  = fraction of nitrogen that is released into the atmosphere as NH<sub>3</sub> or NO<sub>x</sub>,  
(from Table 11.3, Chapter 11 of IPCC, 2006)

$\varepsilon_{factor}$  = emission factor for fertiliser, i.e. kg of N<sub>2</sub>O-N per kg N applied  
(from Table 11.1 chapter 11 of IPCC, 2006)

$M_{N_2O} / M_{N_2} = 44/28$  is the mass ratio of N<sub>2</sub>O and N<sub>2</sub>

$GWP_{N_2O}$  = Greenhouse Warming Potential of N<sub>2</sub>O with respect to CO<sub>2</sub>

The final result is in units of kg CO<sub>2</sub>-equivalents per kg product analysed. The product analysed represents the amount at the stage of interest in the analysis. For example, if emissions for bread are to be calculated, then the different losses from wheat harvest to milled flour and finally to bread should be taken into account. This loss factor is included in  $M_{fertil}$ , and will increase the amount of fertiliser use as the losses increase.

Table II shows examples of emissions calculated by Eq. (1) for different crops. In all cases, the emission factor is 0.01 kg N<sub>2</sub>O-N per kg N applied. This value has changed from the previous IPCC 1996 revised guidelines, in which it was 0.0125. New analysis based on a much larger number of measurements has led to the better estimate given in the 2006 IPCC guidelines. The volatilisation fraction is equal to 10%, the same magnitude as previously accepted. When these data are used, the mean value for the emission factor per kg of N applied is 4.18 kg CO<sub>2</sub>-equivalents /kg N. If uncertainties are combined as explained above, the minimum and the maximum values obtained are 1.24 and 12.6 kg CO<sub>2</sub>-equivalents /kg N, respectively. For a mean value of 100 in Table II (as in wheat for example), the uncertainty range is between a minimum of 30 and a maximum of 300 (-70% to +200%, due to the large uncertainty in N<sub>2</sub>O emission factors).

For rice cultivated in flooded conditions, the emission factor per kg N is 0.003 kg N<sub>2</sub>O-N / kg N applied (IPCC, 2006). This value is one-third of that recommended for fertilisation in upland dry fields (because of anaerobic processes inhibiting N<sub>2</sub>O emissions), and therefore the emission intensity per kg paddy rice due to fertilisation is much lower than for other cereal crops. However, as shown below, the contribution of CH<sub>4</sub> for flooded rice is significant, in contrast to upland cereals.

Table II: Amount of N from synthetic fertiliser application, and N<sub>2</sub>O emissions associated with the cultivation of different crops grown using standard practices

	$M_{fertil}$ (kg N applied per ton harvest)	$N_2O_{fertil}$ (kg CO <sub>2</sub> -equivalents per ton harvest)
Winter wheat <sup>a)</sup>	24	100
Spring wheat <sup>a)</sup>	29	121
Rye <sup>a)</sup>	19	80
Oats <sup>a)</sup>	22	92
Wheat <sup>b)</sup>	16	67
Maize <sup>b)</sup>	5	21
Soybean <sup>b)</sup>	1	4
Sunflower <sup>b)</sup>	5	21
Dry peas / lentils <sup>c)</sup>	8	35
Potatoes Sweden <sup>a)</sup>	3,5	15
Grass for hay <sup>a)</sup>	20	85
Paddy rice <sup>d)</sup>	28	35

<sup>a)</sup> Data for fertiliser use and yields in Sweden from Statistiska Centralbyrån (SCB, 2007)

<sup>b)</sup> Data for fertiliser use and yields in Argentina from FAO (2004a) and Instituto Nacional de Tecnología Agropecuaria (INTA, 2007)

<sup>c)</sup> Egypt, fertiliser and production data from FAO (2005a) and FAOSTAT

<sup>d)</sup> Data for India, fertiliser use from FAO (2005b), and yields from <http://faostat.fao.org>

The lower emission values for wheat in Argentina may be related to the amount of fertiliser used and the yield achieved. Absolute values of fertiliser and yields are 40 kg N /ha and 2500 kg wheat /ha in Argentina, and 153 kg N /ha and 6400 kg wheat /ha in Sweden. Jarvis (2000) argues that the more intensive the production, the larger the environmental impact, though this might not be a general rule. In studies on nitrogen balance from dairy production, Bleken et al. (2005) found that intensification increases the nitrogen surplus per unit N fixed in milk. Their conclusion is that extensive farming is a better strategy for mitigating eutrophication in dairy farming.

If urea is used as a synthetic fertiliser, IPCC (2006) includes an additional emission of CO<sub>2</sub> to counteract the carbon captured in the manufacturing process. This approach is eventually relevant when elaborating inventories but we did not include it here to assess emissions in food processes.

### **b) Nitrous oxide (N<sub>2</sub>O) from application of manure on soils**

The amount of N<sub>2</sub>O emitted from application of manure on soils is given by:

$$N_2O_{m,fertil} = M_{manure} * (1 - fr_{atm,m}) * \epsilon_{factor} * (M_{N_2O} / M_{N_2}) * GWP_{N_2O} * N_{manure} \quad (2)$$

where:

$M_{manure}$  = mass of manure needed to produce the amount of product analysed  
(kg manure per kg product analysed)

$fr_{atm,m}$  = fraction of nitrogen from manure applied that is released into the atmosphere as  
NH<sub>3</sub> or NO<sub>x</sub> (from Table 11.3, Chapter 11 of IPCC, 2006)

$\epsilon_{factor}$  = emission factor for converting nitrogen, i.e. kg of N<sub>2</sub>O-N per kg N applied

$M_{N_2O} / M_{N_2} = 44/28$  is the mass ratio of N<sub>2</sub>O and N<sub>2</sub>

$GWP_{N_2O}$  = Greenhouse Warming Potential of N<sub>2</sub>O with respect to CO<sub>2</sub>

$N_{manure}$  = fraction of nitrogen per unit of manure (kg N per kg manure). (Related to  
 $N_{excr,animal}$ , used in the next section on manure management)

The results are given in units of kg CO<sub>2</sub>-equivalents per kg product analysed.

When manure is used as a fertiliser, the emission factor is the same as in the previous case. However, the volatilisation fraction for N in manure is larger (20% according to Table 10.3 in IPCC, 2006). The mean value for the emission factor per kg of N applied in manure is 3.75 kg CO<sub>2</sub>-equivalent kg<sup>-1</sup> N, with minimum and maximum values 1.03 and 11.4 kg CO<sub>2</sub>-equivalent kg<sup>-1</sup> N, respectively. Due to the larger volatilisation, these values are slightly smaller than for synthetic fertilisers. However, different absolute N weights are applied in each case, and then the final results may differ significantly, as can be observed by comparing the examples shown in Table III with those in Table II.

Table III: Manure applied, and N<sub>2</sub>O emissions associated with its use as a fertiliser, for different crops grown using standard practices

	$M_{manure} * N_{manure}$ (kg N applied per ton harvest) <sup>b</sup>	$N_2O_{m,fertil}$ (kg CO <sub>2</sub> -equivalents per ton harvest)
Winter wheat <sup>a</sup>	18	67
Spring wheat <sup>a</sup>	16	61
Oats <sup>a</sup>	23	87
Potatoes <sup>a</sup>	4	15
Grass for hay <sup>a</sup>	19	72

<sup>a)</sup> Data for manure use and yields in Sweden from Statistiska Centralbyrån (SCB, 2007)

<sup>b)</sup> Manure applied data were found in kg N /ha, without disaggregating N content in manure

For the same crop and the same country, the fertilisation with manure seems to give smaller N<sub>2</sub>O emissions (Table III). The difference is large for both winter and spring wheat, but small (and perhaps not significant) for oats, and of the same value for potatoes.

In order to compare with other types of production and location, we can consider the case of citrus fruits in Argentina. According to the data available (FAO, 2004a), 15% of citrus production in the country is achieved by manure fertilisation of around 7 ton/ ha. By assuming 1% of N in manure from dairy cows, this leads to 280 kg CO<sub>2</sub>-equivalents /ha. The same type of production and similar yield is achieved by using 116 kg N/ ha of synthetic fertiliser, which gives N<sub>2</sub>O emissions of 485 kg CO<sub>2</sub>-equivalents /ha. This example also shows larger N<sub>2</sub>O emissions from synthetic fertilisers compared with manure.

### **c) Nitrous oxide (N<sub>2</sub>O) from crop residues applied on soils**

These emissions are released from the additional nitrogen when crop residues are left on soils, and since no-till techniques are becoming common practice in modern agriculture, their contribution might be significant. The calculation for emissions in this item is based on the estimate of N left in the dry matter of the above-ground (AG) and belowground (BG) crop residues. The mass of N in residues per year and hectare,  $M_{N,residue}$ , is given by:

$$M_{N,residue} = Y_{fresh} * f_{dm} * [R_{AG} * N_{AG} + R_{BG} * N_{BG}] \quad (3)$$

where:

$Y_{fresh}$  = yield for crop in fresh weight (kg crop per ha)

$f_{dm}$  = fraction of dry matter (DM) in crop

$R_{AG}$  = ratio of above-ground DM residues to harvested crop DM

$N_{AG}$  = N content of above-ground residues (kg N per kg DM)

$R_{BG}$  = ratio of below-ground DM residues to harvested crop DM

$N_{BG}$  = N content of below-ground residues (kg N per kg DM)

Eq. (3) is a particular case of Equation 11.6 in the IPCC report (2006), where we assumed that no crop residues are burnt and the fraction removed from fields is zero. The ratio of above-ground residues is estimated from the above-ground biomass obtained by empirical estimates expressed in the following linear regression:

$$AG_{dm} = Y_{fresh} * f_{dm} * \text{slope} + \text{intercept} \quad (4)$$

where the slope and intercept are empirical values given in Table 11.2 from IPCC (2006). Then, the ratio  $R_{AG}$  needed in Eq. (3) is obtained by:

$$R_{AG} = AG_{dm} / Y_{fresh} * f_{dm} \quad (5)$$

The below-ground residue dry matter is also obtained from Table 11.2 from IPCC (2006), by using the given ratio of below-ground to above-ground biomass,  $R_{BG-BIO}$ , and multiplying by the ratio of total above-ground biomass to crop yield, which can be simplified and written as a function of the result in Eq. (5):

$$R_{BG} = R_{BG-BIO} * (R_{AG} + 1) \quad (6)$$

Once the content of N in residues is estimated by the application of Eq. (3), the emission intensity is obtained by multiplying by the corresponding mass and GWP factors, giving the result:

$$N_2O_{N,residue} = M_{N,residue} * \epsilon_{factor} * (M_{N_2O} / M_{N_2}) * GWP_{N_2O} * M_{crop} / Y_{fresh} \quad (7)$$

where:

$\epsilon_{factor}$  = emission factor for converting nitrogen into N<sub>2</sub>O (equal to 0.01 kg of N<sub>2</sub>O-N per kg N, from Table 11.1 Chapter 11 of IPCC, 2006)

$M_{N_2O} / M_{N_2} = 44/28$  is the mass ratio of N<sub>2</sub>O and N<sub>2</sub>

$GWP_{N_2O}$  = Greenhouse Warming Potential of N<sub>2</sub>O with respect to CO<sub>2</sub>

$M_{crop}$  = fraction of product analysed per unit of crop harvested (kg crop per kg product analysed)

Table IV shows a sample calculation for N<sub>2</sub>O emissions arising from leaving 100% of crop residues on the soil. If a different percentage is known to be left on the ground, then the result would be directly proportional to that percentage.

*Table IV: Yields, fraction of above-ground residues and N<sub>2</sub>O emissions for different crops*

	Harvest yield $Y_{fresh}$ (kg per ha)	Harvest dry matter (kg DM per ha)	Above-ground residues (kg DM per ha)	Emissions $N_2O_{N,residue}$ (kg CO <sub>2</sub> -equivalents per ton harvest)
Yellow peas <sup>a</sup>	3000	2670	3860	64
Wheat <sup>a</sup>	6400	5700	9120	63
Oats <sup>a</sup>	4000	3560	4130	52
Potato <sup>a</sup>	28000	6140	1670	9
Soybean <sup>b</sup>	2700	2460	3640	66

<sup>a)</sup> Data for Sweden from SCB (2007)

<sup>b)</sup> Data for Argentina from FAO ([www.faostat.fao.org](http://www.faostat.fao.org))

The resulting emissions of N<sub>2</sub>O from residues of cereal products and potatoes are smaller but comparable to those found from fertiliser application, either from manure or synthetic forms. However, for soybean the emissions from residues are much higher (an order of magnitude) than that from fertilisation, and in the case of peas the difference is around a factor of 2. Thus in evaluating emissions from crops that need little fertilisation, such as N-fixing crops, the contribution from residues must be specially considered.

### **d) Nitrous oxide (N<sub>2</sub>O) from storing or handling manure (AWMS, Animal Waste Management Systems)**

Manure produced in livestock production is managed in a variety of forms. To assess emissions for a given amount of food produced, the resulting emissions per animal  $N_2O_{AWMS,animal}$  from processing of manure under all AWMS possibilities should be calculated as:

$$N_2O_{AWMS,animal} = M_{manure,AWMS} * GWP_{N_2O} * (M_{N_2O} / M_{N_2}) * N_{excr,animal} * \sum_j fr_{animal,j} * \varepsilon_{factor,j} \quad (8)$$

given in units of CO<sub>2</sub>-equivalents per kg product analysed, and with the symbols representing,

$M_{manure,AWMS}$  = amount of manure managed by all AWMS methods to produce the amount of product analysed (kg manure per kg product analysed ).

$GWP_{N_2O}$  = Greenhouse Warming Potential of N<sub>2</sub>O, in CO<sub>2</sub>-equivalents

$\varepsilon_{factor,j}$  = emission factor for converting nitrogen into N<sub>2</sub>O (i.e. kg of N<sub>2</sub>O-N per kg N managed) for the management AWMS of type  $j$

$M_{N_2O} / M_{N_2} = 44/28$  is the mass ratio of N<sub>2</sub>O and N<sub>2</sub>

$fr_{animal,j}$  = fraction of excretion of animal type  $i$  managed as the particular AWMS type  $j$

$N_{excr,animal}$  = amount of nitrogen excreted in manure by animal type  $i$  (kg N per kg manure)

In the *Tier 1* method, an average for the fractions and the emission factors needed for summing up in Eq. (8) are given in IPCC (2006). These data are provided by regions and type of production. Anaerobic liquid methods present the lowest emission factors for N<sub>2</sub>O, aerobic solid storage or dry composting the highest (Table 10.21, Chapter 10 of vol. 4, in IPCC, 2006).

In Table V, a sample calculation for cattle and pigs is considered. The emission factors and the percentages for the different AWMS were obtained from IPCC for European standards, and the manure production per animal are data from Sweden. The last two columns show emissions resulting from Eq. (8), for each animal type and per ton of manure managed and year. Anaerobic or wet managed systems do not produce large amounts of nitrous emissions but they can be very high in methane (as it will be shown in subsequent sections).

The combined uncertainties in these cases give a global asymmetric uncertainty (-)36% to (+)65% for dairy results, and (-)41% to (+)73% for meat cattle and pigs, on the emissions given in the two last columns of Table V. Percentage uncertainties are the same for both cases but the combined uncertainties depend of the sum of products, which are different for every case (see Eq. A.2 in the Appendix).

Considering the production of milk per year (8000 kg) and the emissions of N<sub>2</sub>O shown in Table V for AWMS of dairy cows, the contribution results in 0.053 kg CO<sub>2</sub>-equivalents / kg

milk (uncertainty range: minimum value 0.022 and maximum 0.16 kg CO<sub>2</sub>-equivalents /kg milk).

Cattle produced for meat consumption in Sweden often have carcass weights of 280, 300 or 325 kg, depending on how they are fed, and live between 14 and 18 months (SCB, 2007). We used the average of these three categories, 300 kg carcass weight (average liveweight is around 570 kg) and an average lifetime of 16 months for the calculations of emissions per kg of meat. Table V gives an average emission factor of 1.07 kg CO<sub>2</sub>-equivalents /kg carcass meat for N<sub>2</sub>O emissions from manure management (with an uncertainty range from a minimum of 0.45 to a maximum of 3.26 kg CO<sub>2</sub>-equivalents /kg carcass meat).

Table V: Example of AWMS and N<sub>2</sub>O emissions for dairy cows and pigs

		Liqu. syst.	Solid system	Pit under confinement	Pas-ture range	Others, without emission	N <sub>2</sub> O emissions per ton manure (kg CO <sub>2</sub> -eq per ton manure)	N <sub>2</sub> O emissions per animal (kg CO <sub>2</sub> -eq per animal and year)
	Emission factor (kg N <sub>2</sub> O per kg manure)	0.005	0.005	0,002	0.02	0		
Manure from dairy cattle		36 %	37 %	0	20%	7% <sup>a</sup>	37.5	424 <sup>c</sup>
Manure from other cattle		25%	39%	0	32%	2% <sup>a</sup>	47.5	323 <sup>f</sup>
Manure from slaughter pigs		0	14 %	72 %	0	14% <sup>b</sup>	24.3	12 <sup>d</sup>
Manure from breeding pigs		0	14 %	72 %	0	14% <sup>b</sup>	24.3	56 <sup>e</sup>

<sup>a)</sup> Corresponds to manure used as fertiliser (accounted for in another category)

<sup>b)</sup> 9% corresponds to anaerobic lagoons with no emissions (IPCC, 2006), and 5% used as fertiliser

<sup>c)</sup> Average for dairy cows in Sweden, 11 300 kg manure per animal and year (SCB, 2007)

<sup>d)</sup> Average for market pigs in Sweden, 483 kg manure per animal and year (SCB, 2007)

<sup>e)</sup> Average for reproduction pigs in Sweden, 2310 kg manure per animal and year (SCB, 2007)

<sup>f)</sup> 6790 kg manure per animal and year, derived from IPCC amount of N excreted per animal and day

To assess N<sub>2</sub>O emissions from pig manure, we considered a carcass weight of 85.7 kg and a life of around half a year (0.54 year). With the help of Table V we obtained an emission

factor for N<sub>2</sub>O of 0.07 kg CO<sub>2</sub>-eq /kg carcass pig meat (with uncertainty range from 0.044 to 0.13). This value is small compared with beef, and this is due to the manure storage systems routinely used for pig production, which are low in N<sub>2</sub>O emissions but high in methane, as it will be observed in the next section.

For poultry, the emission factor for N<sub>2</sub>O from AWMS given by IPCC (2006) is 0.001 kg N<sub>2</sub>O-N / Kg N, which is much smaller than any of the emission factors in Table V. This lead to an emission per animal and year of 0.19 kg CO<sub>2</sub>-equiv., and considering an average poultry of 1.8 kg carcass slaughtered at 35 days, it gives an emission intensity for N<sub>2</sub>O of 0.010 kg CO<sub>2</sub>-equiv./ kg carcass meat. This value is much smaller than for beef or pork.

### e) Contribution of methane (CH<sub>4</sub>) from manure storage

The storage of manure, particularly in anaerobic conditions, produces substantial amount of methane. The emission factors in *Tier 1* are given per animal and year (IPCC, 2006), and the values depend on the climate and production standards. The emission intensity per animal,  $CH_4_{CH_4, animal}$ , for producing the amount of food analysed, is:

$$CH_4_{CH_4, animal} = M_{manure} * \epsilon_{CH_4, animal} * GWP_{CH_4} / M_{manure, animal} \quad (9)$$

in units of CO<sub>2</sub>-equivalent per kg manure and year for a given animal.

The symbols represent:

$\epsilon_{CH_4, animal}$  = emission factor for CH<sub>4</sub> per animal per year

$M_{manure, animal}$  = mass of manure per animal per year

$M_{manure}$  = mass of manure needed to produce the amount of product analysed  
(kg manure per kg product analysed )

Table VI shows methane emissions arising from manure for different animals. We chose examples of animals and products for Western Europe, and the data from IPCC (2006) used in Table VI are the average for a temperate region. The emissions in units of CO<sub>2</sub>-equivalents are those directly given by IPCC per animal and year, multiplied by 25 (the GWP for a 100-year period given in Table I). The mean values for producing milk, eggs and meat are for Sweden (SCB, 2007). Beef calculations took into account the average of three slaughter categories, as explained in the previous section on AWMS.

The uncertainties in these values derive mainly from the uncertainty in the emission factor, which is ±30% (IPCC, 2006). Then, for milk the uncertainty ranges from a minimum of 0.12 to a maximum of 0.22 kg CO<sub>2</sub>-equivalents kg<sup>-1</sup> milk. For beef the 30% uncertainty leads to a minimum of 1.24 to a maximum of 2.31 kg CO<sub>2</sub>-equivalents kg<sup>-1</sup> carcass.

Table VI: CH<sub>4</sub> emissions from manure and the influence in different food products

	Emission factor, kg CO <sub>2</sub> -eq per head and year	Food product analysed	Production of food analysed kg product per head and year	Methane emissions, kg CO <sub>2</sub> -eq per kg product
Dairy cattle	1375	Milk	8000 <sup>c</sup>	0.17
Non-dairy cattle	400	Beef	300 <sup>d</sup>	1.78 <sup>e</sup>
Poultry eggs WM <sup>a</sup>	35	Eggs	20	1.75
Poultry eggs DMM <sup>b</sup>	0.75	Eggs	20	0.037
Poultry broilers	0.5	Meat	1.8	0.003 <sup>f</sup>
Turkey	2.25	Meat	14	0.056 <sup>g</sup>
Slaughter pigs	325	Pork	85.7	2.06 <sup>h</sup>

a) WM means wet manure management

b) DMM means dry manure management

c) Milk production for Sweden, around 8000 kg milk per cow and year (SCB, 2007)

d) Average beef production for Sweden, for 16 months slaughter bulls (SCB, 2007)

e) The ratio of 16 months to 12 months was applied

f) For animal lifespan of 0.096 year (data from Svensk Fågel)

g) For animal lifespan of 0.346 year (data from [www.livsmedelssverige.org](http://www.livsmedelssverige.org))

h) For animal lifespan of 0.54 year (data from [www.livsmedelssverige.org](http://www.livsmedelssverige.org))

Pork meat presents the highest value for the emission intensity of CH<sub>4</sub> from manure management, a value of 2.06 kg CO<sub>2</sub>-equivalents / kg carcass meat, with an uncertainty leading to a minimum value of 1.44 and a maximum of 2.67 kg CO<sub>2</sub>-equivalents / kg pork carcass. Poultry and turkey meats present the lowest CH<sub>4</sub> emission intensities. This is due to the management of manure in a dry form, which was considered in Table VI. The values for CH<sub>4</sub> can be very different if the manure is managed in wet forms, as it can be observed for eggs, where we show examples for both options. The IPCC report does not mention the use of wet manure in the case of broilers and turkey.

The values shown in Table VI can be compared with the N<sub>2</sub>O emissions from manure found in the previous section. For both milk and meat, CH<sub>4</sub> emissions from manure handling are higher than N<sub>2</sub>O from manure management, especially for milk which is a factor of 3 higher. In the next section we calculate the influence of enteric fermentation in CH<sub>4</sub> emissions.

### **f) Contribution of methane (CH<sub>4</sub>) from enteric fermentation**

Emissions of methane from enteric fermentation are especially large when it comes to ruminants, and depend upon the quality of feed given to the animals. Here we use average

data published by IPCC (2006) within the *Tier 1* method, which relates to the food product analysed by the following equation:

$$CH_{4\text{ ef,animal}} = \varepsilon_{\text{ef,animal}} * GWP_{CH_4} / M_{\text{product}} \quad (10)$$

where  $CH_{4\text{ ef,animal}}$  = CH<sub>4</sub> production per animal in *enteric fermentation (ef)*, in units of CO<sub>2</sub> equivalent

$\varepsilon_{\text{ef,animal}}$  = default emission factor to produce CH<sub>4</sub> in *ef*, per head of animal

$GWP_{CH_4}$  = Greenhouse Warming Potential of CH<sub>4</sub> with respect to CO<sub>2</sub>

$M_{\text{product}}$  = amount of product analysed per head of animal

Table VII considers examples of emissions from enteric fermentation associated with the production of milk and meat in Sweden. In the *Tier 1* methodology, the emission factors are given by the IPCC (2006) directly in kg of CH<sub>4</sub> per animal and year, which for Western Europe are: 109 for dairy cows, 57 for non-dairy cattle, 8 for sheep, and 1.5 for market pigs. The corresponding kg CO<sub>2</sub>-equivalents is shown in the second column of Table VII, where a value of GWP of 25 was used (from Table I in the present report).

*Table VII: CH<sub>4</sub> emissions from enteric fermentation for different animal foods obtained*

	Emission factor, kg CO <sub>2</sub> -eq per head and year	Food product analysed	Production of food analysed kg product per head and year	Methane emissions, kg CO <sub>2</sub> -eq per kg product
Dairy cattle	2725	Milk	8000 <sup>i</sup>	0.34
Non-dairy cattle	1425	Beef	300 <sup>j</sup>	6.33 <sup>k</sup>
Lamb	200	Lamb	20.5	4.88 <sup>l</sup>
Slaughter pigs	37	Pork	85.7	0.24 <sup>m</sup>

<sup>i)</sup> Milk production for Sweden, around 8000 kg milk per cow and year (SCB, 2007)

<sup>j)</sup> Average beef production for Sweden, for 16 month slaughter bulls (SCB, 2007) and in carcass weight (slaughter liveweight average 570 kg)

<sup>k)</sup> The ratio of 16 months to 12 months was applied

<sup>l)</sup> The average lifespan is 0.5 year and the carcass weight 20.5 kg (SCB, 2007)

<sup>m)</sup> A pig lifespan of 0.54 year was used (SCB, 2007)

The uncertainties in these emissions are ±40%, which is the total uncertainty for the emission factors given by the IPCC (2006). Methane emissions associated with milk range between 0.20 to 0.48 CO<sub>2</sub>-equivalents /kg milk; while for beef the uncertainty range goes from a minimum of 3.80 to a maximum of 8.90 kg CO<sub>2</sub>-equivalents/ kg carcass meat. Pigs produce much smaller emissions than ruminants, and the emission intensity from enteric fermentation found for lamb was similar to that for beef (4.88 kg CO<sub>2</sub>-equivalents /kg carcass lamb meat, with a range of uncertainty leading to a minimum of 2.93 and a

maximum of 6.83). We did not consider poultry in this section because the IPCC reports that there are not enough data to make an assessment.

### **g) Contribution of CH<sub>4</sub> from rice cultivation**

Flooded agricultural fields are most common in rice production. It is estimated that more than 80% of rice produced worldwide is under flooded conditions. Rice can also be cultivated in dry upland areas. Flooding has two main purposes: helping cultivation by natural control of pests and weeds, and using naturally occurring flooded areas to produce food. Default emission values should account for flooding regime (times of drainage and aeration), pre-season treatment of land, and irrigation regime (rainfed or not). The emissions from methane associated with the production of paddy rice,  $CH_4_{rice}$ , are given by,

$$CH_4_{rice} = M_{rice} * \epsilon_{rice} * d_{flood} * f_{flood} * f_{pre} * GWP_{CH_4} / y_{rice} \quad (11)$$

in units of CO<sub>2</sub>-equivalents per kg product analysed, with the following terms:

- $M_{rice}$  = amount of paddy rice harvested for the amount of product analysed  
(kg paddy rice harvested per kg product analysed)
- $\epsilon_{rice}$  = methane default emission factor for flooded rice fields (kg CH<sub>4</sub> per ha and day)  
(Table 5.11 of IPCC, 2006)
- $d_{flood}$  = number of days in which the field is flooded
- $f_{flood}$  = fraction accounting for flooding regime under cultivation period (range 0 to 1, i.e. upland fields is 0 (dry), and always flooded 1, Table 5.12 from IPCC, 2006)
- $f_{pre}$  = fraction for the flooding regime in pre-season (before planting) (from Table 5.13 IPCC, 2006)
- $GWP_{CH_4}$  = Greenhouse Warming Potential of methane
- $y_{rice}$  = yield of rice per season (kg per ha)

To assess the emissions from practical rice cultivation, we obtained data for production regimes and yields from USA and Thailand. These two countries were chosen because they have very different water sources, techniques and final yields, and therefore they are representative of diverse conditions. Table VIII shows the data used and the resulting CH<sub>4</sub> emissions given by Eq. (7).

The average CH<sub>4</sub> emissions resulting from rice fields USA and Thailand are (0.50+0.55)/2 = 0.525 kg CO<sub>2</sub>-equivalent / kg paddy rice, with an uncertainty range between a minimum of 0.25 to a maximum value of 0.90. This can be compared with previous data from inventories in India and Japan. Garg et al. (2006) report that for a production of 1.34 10<sup>11</sup> kg in India, emissions of 8.6 10<sup>10</sup> kg CO<sub>2</sub>-equivalents from methane were calculated. This leads to an average of 0.64 kg CO<sub>2</sub>-equivalent /kg paddy rice for India. Breiling et al. (2005) analysed data from Japan, resulting in 0.59 kg CO<sub>2</sub>-equivalent / kg paddy. Both are in agreement with

the calculation in *Tier 1* achieved in the present work, and within the range of uncertainty. The main uncertainty from conceptualisation here would be the aggregated values used for pre-season treatment and for flooding conditions. Furthermore, the number of days under flooding conditions could possibly be smaller, as reported by Towprayoon et al. (2005) for Thailand (less than 108 days). In any case, the accuracy of the results can be considered sufficient for the purposes of the present work.

*Table VIII: Methane emissions from rice fields for Thailand and the USA*

	Water management system	Emission factor, kg CH <sub>4</sub> per ha $\epsilon_{rice} * d_{flood}$	Fraction flooding regime $f_{flood}$	Fraction for pre-season flooding $f_{pre}^d$	Yield kg paddy rice per ha $y_{rice}$	CH <sub>4</sub> emissions, kg CO <sub>2</sub> -eq per kg paddy rice
USA	100% irrigated	156 <sup>a</sup>	0.78 <sup>b</sup>	1.22	7400 <sup>e)</sup>	0,50
Thailand	7% irrigated	156 <sup>a</sup>	0.78 <sup>b</sup>	1.22	2640 <sup>e)</sup>	0,55
	92% rain fed	156 <sup>a</sup>	0.27 <sup>c</sup>	1.22		

<sup>a)</sup> The value given by IPCC is 1.3 kg CH<sub>4</sub> per day and ha, while other research works assume 120 days under flooding conditions (for example Minamikawa and Sakai, 2006)

<sup>b)</sup> Irrigated, aggregated case

<sup>c)</sup> Rainfed, aggregated case

<sup>d)</sup> Aggregated case for pre-season

<sup>e)</sup> Reference FAOSTAT (<http://faostat.fao.org>)

The fertilisation of rice can also give non-CO<sub>2</sub> emissions. However, in flooded conditions anaerobic processes reduce N<sub>2</sub>O emissions significantly, which is in line with an emission factor one-third of that for upland crop fertilisation. Then, the CH<sub>4</sub> emissions found for rice cultivation are the main GHG for this crop, and they are higher than the N<sub>2</sub>O emissions found for upland cereals (see Table II for a comparison). Upland rice would have no CH<sub>4</sub> emissions and a contribution of N<sub>2</sub>O that can be estimated as similar to that of other cereals.

## Non-CO<sub>2</sub> greenhouse emissions from some food products — a comparison

Having presented emission factors for non-CO<sub>2</sub> greenhouse gases in various stages of the agricultural phase we now present some estimates of the aggregated emissions of such gases

for some animal and vegetable food products. Emissions of N<sub>2</sub>O from fertilisation, crop residues and manure management are included as are emissions of CH<sub>4</sub> from manure management, enteric fermentation and rice cultivation. For the animal products analysed, we consider emissions during cultivation of the fodder required for rearing the animals when making these estimates. For the vegetable products we consider only emissions during cultivation.

## ***Animal products***

Considering the fodder requirements for milk cows, about 3500 kg of grass, 2000 kg of cereals and 1000 kg of protein fodder per year, the non-CO<sub>2</sub> emissions associated with producing that are derived from Table II, and are 655 kg CO<sub>2</sub> equiv./animal and year, when combined fertilisation and residues left on field are considered. With a milk production of 8000 kg/animal.year, the contribution from fodder is 0.082 kg CO<sub>2</sub>-eq./ kg milk. Then, the emissions from manure and enteric fermentation have to be added. N<sub>2</sub>O emissions from manure management in dairy cows in Western Europe (example in Table V) leads to 0.053 kg CO<sub>2</sub>-eq./ kg milk, while emissions of CH<sub>4</sub> account for 0.17 in the case of methane from manure and 0.34 kg CO<sub>2</sub>-eq./ kg milk in the case of enteric fermentation (EF) (details in Tables VI and VII). Then, the total non-CO<sub>2</sub> emissions associated with the production of milk are  $(0.082 + 0.053 + 0.17 + 0.34) = 0.64$  kg CO<sub>2</sub> -equiv./kg milk (at the dairy farm step), and combined uncertainties giving a minimum value of 0.50 and a maximum of 0.85). In the case of dairy, EF contributes with much larger emissions, accounting for 53% of total non-CO<sub>2</sub> emissions for producing milk, followed in relevance also by CH<sub>4</sub> from manure handling with 26%, fodder fertilisation and residues 13% and the relatively smaller contribution of 8% from N<sub>2</sub>O from manure management.

When a similar calculation is made for beef, here assumed to consume 10 kg of fodder per kg carcass meat, the result is 1.25 kg of CO<sub>2</sub> equivalents/kg carcass meat for the fodder production. Uncertainties are in the order of 0.38 and 3.80. Using results from Tables V, VI and VII, non-CO<sub>2</sub> emissions in the production of bovine meat account for  $(1.07 + 1.78 + 6.33) = 9.20$  kg CO<sub>2</sub>-equiv./ kg carcass meat, with a range obtained from combined uncertainties having a minimum of 6.25 and a maximum of 12.13 kg CO<sub>2</sub>-eq./kg carcass. When the fodder is added, a total of 10.44 kg CO<sub>2</sub>-eq./kg carcass meat is found, with a minimum of 8.23 and a maximum of 13.7 kg CO<sub>2</sub>-eq./ kg carcass. For bovine meat, the emissions are dominated by EF (61%), followed by methane emitted in manure management (17%), and N<sub>2</sub>O emissions in fodder production (12%) and in manure management (10%).

The values found here for non-CO<sub>2</sub> emissions for milk and beef are higher than the previously reported ones for greenhouse emissions associated with the energy imbedded in producing the foods. Therefore, the additional non-CO<sub>2</sub> greenhouse emissions could strengthen conclusions made when comparing environmental impacts of diets containing substantial amounts of meat and dairy products (Wallén et al, 2004).

In the case of pork meat, the estimation for fodder and the data showed in Tables V, VI and VII lead to  $(0.38 + 0,07 + 2.06 + 0.24 ) = 2.75$  kg CO<sub>2</sub>-eq./kg carcass pork meat, with combined uncertainties leading to a minimum value of 2.07 and a maximum of 3.73. Production of pork fodder accounts for 14% of emissions, being the main contributor CH<sub>4</sub> from manure management with 75%, while enteric fermentation accounts for 9% and N<sub>2</sub>O from manure management is relatively small (3%). The emissions found for pork are in agreement with previous estimations by Carlsson-Kanyama (1998) and Wallén et al. (2004), both assessing a total of around 6 kg CO<sub>2</sub>-eq./kg carcass meat when also energy CO<sub>2</sub> contributors were included.

At present there is no information on enteric fermentation from chicken. CH<sub>4</sub> emissions from manure are very different if a wet or dry management is considered. When manure is managed as liquid in anaerobic lagoons methane emissions are 46 times higher than that for dry management. In the case of broilers, and following IPCC suggested emission factors, a dry management is considered here, with emissions of 0.02 kg CH<sub>4</sub> /head and year. The contribution from fodder cultivation is the largest, accounting for 94% of the emissions in broilers meat, and contributions of 5% from N<sub>2</sub>O and only 1% from CH<sub>4</sub> in manure management. Accordingly, the emissions found for broilers meat are 0.26 kg CO<sub>2</sub>-equiv./kg carcass meat, with an uncertainty given a minimum value of 0.09 to a maximum of 0.74.

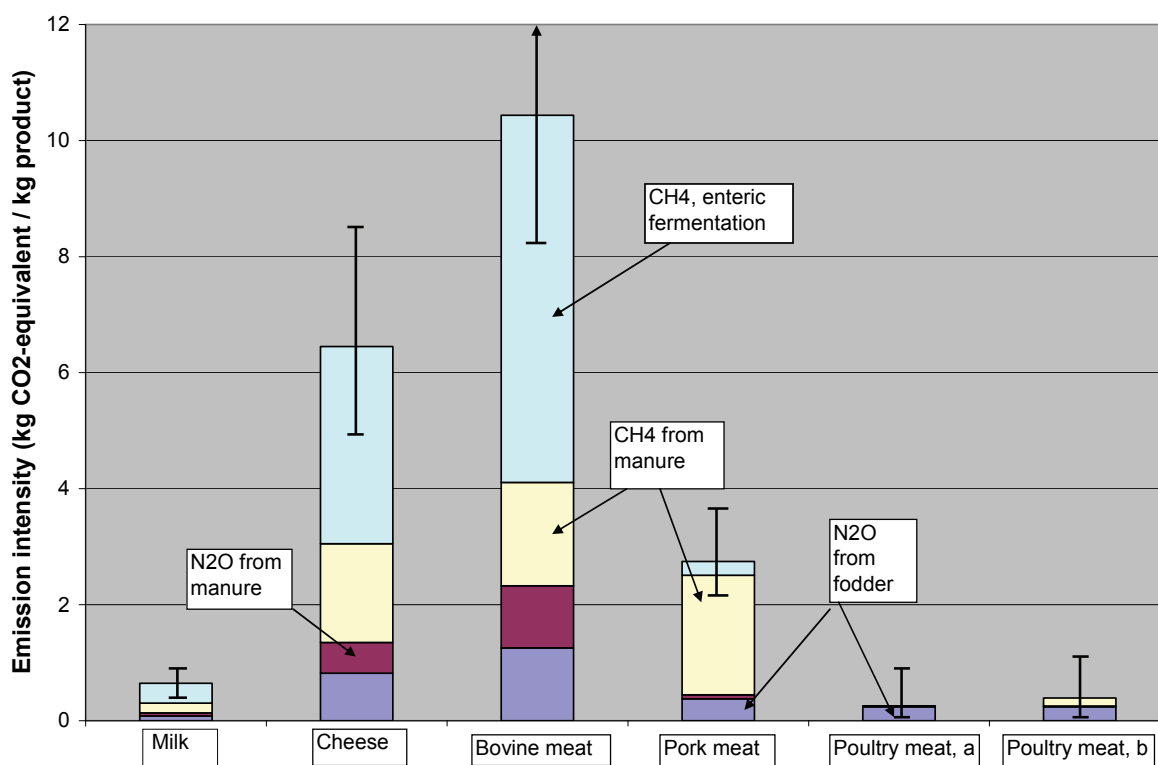


Figure 1: Absolute values of non-CO<sub>2</sub> emission intensities for different animal products.

These four examples showed the diversity of variables and their relative weights influencing non-CO<sub>2</sub> greenhouse gas emissions; and in addition, the comparison for meats leads to the understanding of the important role of enteric fermentation in total emissions. Figure 1 shows the results for the animal foods discussed above. We have also added cheese, produced by using 10 kg of milk for 1 kg of cheese, in this comparison. The influence of enteric fermentation can be observed. Poultry meat presents the lowest emissions compared to the other meats in Figure 1. We have introduced two options for poultry, a) and b). In a) we display the emission values as explained above, with manure managed in a dry way. To assess the change in emissions if the manure would be handled wet, we have increase CH<sub>4</sub> emissions for broilers manure taken the emissions suggested by IPCC (2006) for wet handling from egg-lying hens, which is a factor of 46 larger. Nevertheless, total emissions from non-CO<sub>2</sub> gases are relatively low in either poultry option. The large variation among different animal foods can be observed.

Error bars account for the total uncertainty, combining individual uncertainties for each term in the sum as explained above and in the Appendix. For bovine meat the upper limit is out of the graph (13.7 kg CO<sub>2</sub>-equivalents / kg carcass meat).

In Figure 2, the relative relevance of the N<sub>2</sub>O and CH<sub>4</sub> emissions from different sources is displayed.

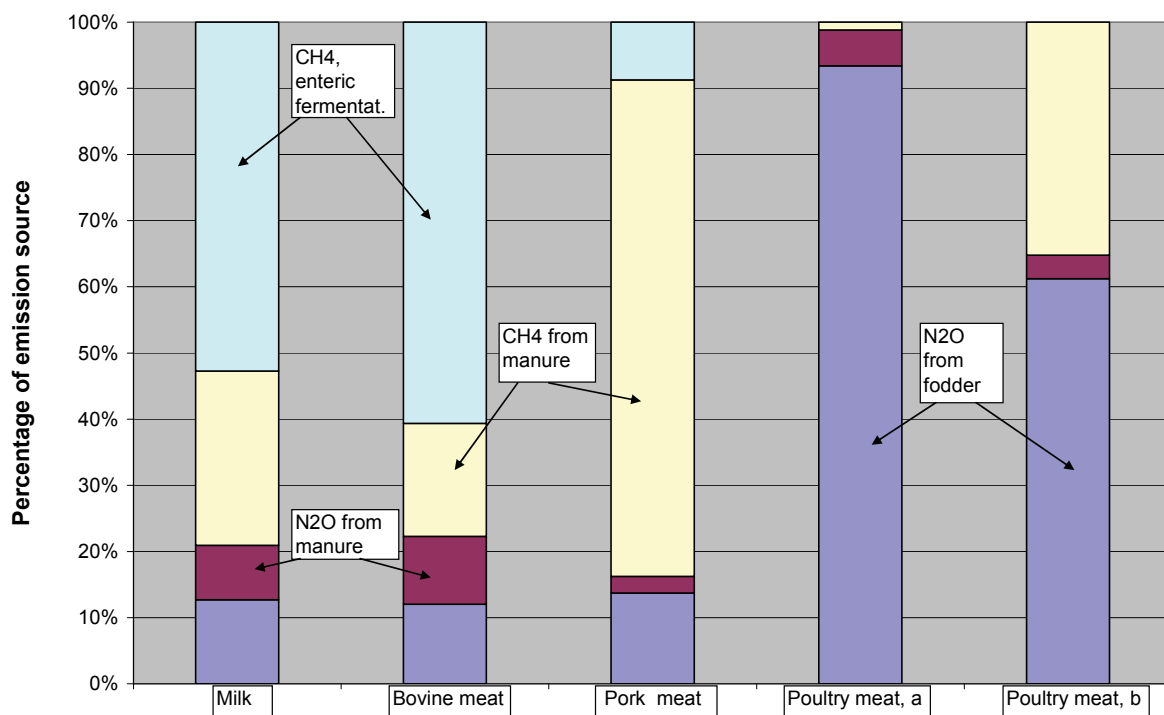


Figure 2: Relative importance of the various sources of non-CO<sub>2</sub> emissions for different animal products.

Figures 1 and 2 illustrate the influence of different processes in livestock production leading to non-CO<sub>2</sub> greenhouse emissions, and the results can be useful in assessing potential for improvements in production techniques towards lower emissions. Clearly, methane is the

most important contributor in animal rearing, whether from manure management and from enteric fermentation. The two possibilities considered for poultry also show the importance of adopting a cleaner production technique.

## Vegetable products

Cultivation of cereals contributes to about 0.15 kg CO<sub>2</sub> equivalents per kg of crop when emissions from fertilisation and crop residues are considered, with uncertainties in the range of 0.05 to 0.4. For potatoes and legumes (such as soybeans) results are very low, less than 0.035 kg CO<sub>2</sub>-eq. / kg harvest. Cultivation of rice under flooding conditions (most of paddy area worldwide) gives rise to higher emissions due to methane; however N<sub>2</sub>O emissions from fertiliser are in the case of flooded rice very small. From Table VII, methane emissions for rice accounts for 0.52 kg CO<sub>2</sub>-eq. / kg paddy with uncertainties in the order of 0.25 at a minimum to 0.90 kg CO<sub>2</sub>-eq. /kg paddy a maximum expected emission, and from Table II, and additional 0.035 kg CO<sub>2</sub> equiv. / kg paddy from fertilisation should be added (with uncertainties leading to a minimum of 0.01 and a maximum of 0.10 kg CO<sub>2</sub> equiv./kg paddy).

Figure 3 shows the results for some food products with uncertainties displayed. Results for bovine meat and cheese were not included but were displayed in Figure 1.

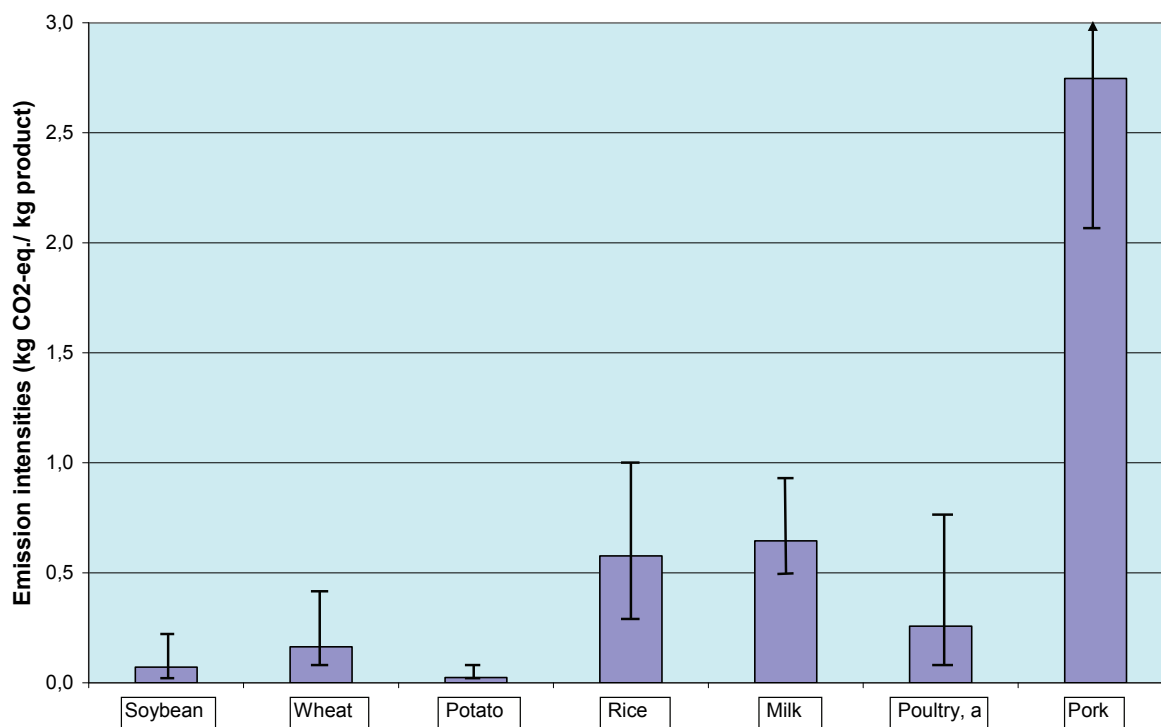


Figure 3: Non-CO<sub>2</sub> emission intensities for different foods discussed in the text. The error bars give the confidence range in each case. For pork the upper limit is out of the graph (3.73 kg CO<sub>2</sub>-eq./kg carcass meat).

The comparison is for primary products only and for a detailed quantitative analysis with consumer relevance functional food units must be considered (Carlsson-Kanyama, 1998). However, results for primary products show that even when uncertainties are considered, most animal products cause far higher greenhouse emission than foods from plant origin (except for rice), when only non-CO<sub>2</sub> greenhouse gases are considered. Protein from plant origin, like soy, presents very low non-CO<sub>2</sub> emissions. Similar conclusion is drawn for wheat: low emissions associated with a concentrated dry vegetable food. Poultry meat presents reasonably low emissions, even if we consider the more polluting case with wet manure handling (as in the previous figures).

## Appendix: Equations for combining uncertainties

This method is based on error propagation of variables with no correlation (or weak correlation), and the uncertainties should be equal to or smaller than 30%. With higher uncertainties the method is not as accurate but gives approximate results that can be corrected.

For multiplication of variables with individual uncertainties  $U_k$ , the total uncertainty for the resulting product of variables is:

$$U_{total} = \sqrt{\sum_k U_k^2} \quad (\text{A.1})$$

where  $U_k$  is the percentage uncertainty (half the 95% confidence interval divided by the mean value and expressed as a percentage), associated with each of the quantities. Equation (A.1) is not valid for divisions.

When uncertain quantities are combined by addition and subtraction, the total uncertainty is given by,

$$U_{total} = \sqrt{\sum_k U_k^2 * X_k^2} / \left| \sum_k X_k \right| \quad (\text{A.2})$$

with  $U_k$  having the same meaning as in Eq. (A.1), and the mean value of the quantity. If the individual uncertainties are larger than 30% or there are asymmetric uncertainty intervals, better estimates can be achieved by correcting the results using the equations given in section 3.7.3 of IPCC (2006).

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