average percentages of savanna burned annually, as shown in Table 4-14. Based on the area and type of savanna burned, the amount of carbon released can be calculated (a reflection of biomass densities, fractions burned, carbon contents and fractions oxidised). The second component of the calculation is the same as for other biomass burning categories – emission ratios are applied to estimate the amount of trace gas released based on the amount of carbon released (Table 4-15 provides default emission ratios).

### TABLE 4-14
### REGIONAL SAVANNA STATISTICS

| Region[a] | Fraction of Total Savanna that is Burned Annually | Aboveground Biomass Density (t dm/ha) | Fraction of Biomass Actually Burned | Fraction of Aboveground Biomass that is Living |
|---|---|---|---|---|
| Tropical America | 0.50 | 6.6 ±1.8 | | |
| Tropical Asia | 0.50 | 4.9 | | |
| Tropical Africa | 0.75 | 6.6 ±1.6 | | |
| Sahel zone | 0.05-0.15[b] | 0.5-2.5[b] | 0.95 | 0.20 |
| North Sudan zone | 0.25-0.50[b] | 2-4[b] | 0.85 | 0.45 |
| South Sudan zone | 0.25-0.50[b] | 3-6[b] | 0.85 | 0.45 |
| Guinea zone | 0.60-0.80[b] | 4-8[b] | 0.9-1.0 | 0.55 |
| Australia | 0.05-0.70 | 2.1-6 | | |

Sources: Hao et al., 1990, except where noted. These figures are growing season average biomass values, considered most appropriate for general default values

[a] Note that these are ecological zones that do not correspond directly to areas with political boundaries of the same name. For example, the North and South Sudan zones include countries other than Sudan and run East-West across the African continent.

[b] Menaut et al. (1991) These figures are maximum biomass values. For these arid sub-regions, maximums are considered the most appropriate default values.

Note: Biomass density is in tonnes of dry matter (dm) per hectare (ha).

The approach recognises that countries generally possess more than one savanna type, each with different characteristics, such as vegetative cover, that would affect trace gas emissions from burning. Also, the savanna area within a country may not be burned all at once, but rather in stages over the course of the dry season. Since the amount and nature (e.g., moisture content) of the vegetation changes during the year, factors such as biomass exposed to burning and fraction burned will vary among the savanna areas burned at different times. The data requested by this methodology focus upon country-specific types of savannas and the country-specific rate of burning for each type.[21]

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[21] If the area of savanna is not readily available, then the area of "open, broad-leaved forests," including open, broad-leaved, fallow areas, as defined by the UN Food and Agriculture Organization in FAO (1993) can be used as an estimate. This land area, corresponds to "mixed broad-leaved forest-grassland tree formations with a continuous dense grass layer in which the [woody vegetation covers] more than 10% [of the area]" (Lanly, 1982). FAO (1993) provides 1990 estimates of this area, by country, for tropical America, Asia, and Africa. Hao et al. (1990) provide an estimate of the humid savanna area in Australia, based on work by Lacey et al. (1982).

It is also recognised that national and regional estimates of the percentage of savanna area burned annually are highly uncertain. An example selection of regional estimates is included in Table 4-14. Though regional variability is great, the methodology, by focusing upon a simple classification of savanna type and the burning by type, can be implemented using data that are available to most countries. The methodology is intended to be flexible to allow users to define the savanna types and/or geographic subregions for calculations. It is strongly recommended that national experts consider dividing total savannas into woody savannas and grasslands, if possible. Many countries contain some systems which have significant aboveground woody biomass and others which have very little aboveground biomass other than grasses. These subcategories have significantly different biomass densities and fractions oxidised and should be accounted for separately rather than by averaging, if data are available. National experts are encouraged to carry out the calculations at the finest levels of detail for which credible data can be obtained. Finally, by varying assumptions about the rate and/or type of savannas burned, national experts can easily compare the sensitivity of the calculated emissions to the uncertainties in the data.

It should be noted that not all savanna burning occurs from anthropogenic causes. Some natural savanna fires obviously occur, and would occur in the absence of human intervention. As is the case with many human interactions with the biosphere, it is very difficult to establish the net effects of human intervention relative to the natural background, or the conditions which would have occurred naturally in the absence of intervention. In this situation, the recommended conservative default is that all fires are considered anthropogenic, unless they can be documented to be from natural causes. This clearly may overstate the emissions somewhat. National experts may choose to modify this assumption using expert judgement or other sources to allocate the anthropogenic and natural components, provided the rationale is clearly documented.

### Step 1: Total Carbon Released From Savanna Burning

In order to calculate the carbon released to the atmosphere from savanna burning, these data are required for each category:

- Area of savanna;
- Fraction of savanna area burned annually;
- Average aboveground biomass density (tonnes dry matter/hectare) of savannas;
- Fraction of aboveground biomass which actually burns;
- Fraction of aboveground biomass that is living;
- Fraction of living and of dead aboveground biomass oxidised; and
- Fraction of carbon in living and dead biomass.

Not all of these data must be provided by the user. Initially one could pool the living and dead biomass if data are not available. More importantly, Table 4-14 provides much of the basic default data that only need to be refined for country-specific relevance. Given the data, the steps to calculate emissions are not overly difficult. One simply calculates from the area burned the total carbon released based upon the factors listed above. In addition to the data in Table 4-14, other recommended default values are included in the step-by-step discussion below.[22]

The following equations summarise the calculations to estimate the total carbon released due to the burning of savannas for each category:

**EQUATION 1**

Area of Savanna Burned Annually (ha)

=

Total Area of Savanna (ha) x Fraction Burned Annually

**EQUATION 2**

Biomass Burned (t dm)

=

Area of Savanna Burned Annually (ha)
x Aboveground Biomass Density (t dm/ha) x Fraction Actually Burned

**EQUATION 3**

Carbon Released from Live Biomass (t C)

=

Biomass Burned (t dm) x Fraction that is Live x Fraction Oxidised
x Carbon Content of Live Biomass (t C/t dm)

**EQUATION 4**

Carbon Released from Dead Biomass (t C)

=

Biomass Burned (t dm) x Fraction that is Dead x Fraction Oxidised
x Carbon Content of Dead Biomass (t C/t dm)

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[22] It is hoped that individual countries have this information since it is needed to execute the proposed methodology. Regional estimates of these statistics are provided by Menaut (1990) and Hao et al. (1990) and reproduced in a table. More country-specific research is clearly needed on this issue before accurate inventories can be developed. This research should include data on savanna area burned annually, savanna biomass densities, live fractions of biomass, burning efficiencies, and carbon contents of savanna biomass. In the meantime, default values can be used.

**EQUATION 5**

Total Carbon Released (t C)

=

C Released from Live Material (t C) + C Released from Dead Material (t C)

In the first equation, the savanna area in the country is multiplied by the percentage of the savanna area that is burned annually, if statistics on area burned annually are not directly available. If national experts have data on the area burned annually they should use this and begin with equation 2. In the second, area burned is multiplied by aboveground dry biomass per hectare (ha) on the savanna at the time of burning and the fraction of biomass which actually burns. Regional estimates of rates of savanna burning and biomass densities are presented in Table 4-14. The fraction actually burned accounts for the fact that when savannas are burned, not all of the biomass on each hectare is actually exposed to flame. If detailed information is not available, a general default value in the range of 0.80-0.85 is recommended (Delmas and Ahuja, 1993).

The aboveground biomass density before burning is a function of the type of savanna being burned and the time of year in which burning occurs.[23] The values for West African savannas provided in Table 4-14 correspond to mid-season fires, except for those of the Sahel where burning occurs early. If statistics on maximum biomass density and fraction of maximum biomass density present at the time of burning are not available, countries can use an average biomass density instead. According to this analysis, average savanna biomass densities are lowest in tropical Asia, at about 5 tonnes per hectare (t/ha) (Singh and Misra, 1978), average around 6.6 t/ha in tropical Africa and tropical America (San José and Medina, 1976; González-Jiménez, 1979; Coutinho, 1982; Hopkins, 1965; Haggar, 1970; Menaut and César, 1982; and Huntley and Morris, 1982). The densities range between 2 and 6 t/ha in Australia (Lacey et al., 1982). These estimates have an uncertainty of ± 30 per cent based on field measurements (Hao et al., 1990). As mentioned, these regional average densities are presented in Table 4-14 and can be used as default values if average biomass density for a specific country or savanna type is not known.

In the third and fourth equations, the living and the dead portions of aboveground biomass burned are multiplied by their respective fractions oxidised and carbon contents. Estimates of the fraction of aboveground biomass that is living for West African savannas range from 20 to 55 per cent (Table 4-14). Data suggest that for the live portion, the fraction which burns ranges between 65 and 95 per cent and for the dead portion essentially 100 per cent burns (Menaut et al., 1991). If fractions oxidised are not available, 80 per cent and 100 per cent for the living and dead portions, respectively, can be used. If country or ecosystem values are not available, then the values 0.45 t C/t dry biomass and 0.40 t C/t dry biomass can be used as default values for the carbon contents of the living and dead portions, respectively (Menaut et al., 1991).

The total carbon released from savanna burning (Equation 5) is estimated by summing the carbon released from the living and the dead biomass fractions, calculated in Equations 3 and 4.

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[23] Menaut et al. (1991) calculate this number by multiplying the maximum biomass density of the savanna (which generally is reached at the end of the growing season) by a coefficient that declines as the burning occurs later in the dry season.

### Step 2: Emissions

Once the carbon released from savanna burning has been estimated, the emissions of $CH_4$, CO, $N_2O$, and $NO_x$ can be calculated using emission ratios. (Default values are presented in Table 4-15.)[24] The amount of carbon released due to burning is multiplied by the emission ratios of $CH_4$ and CO relative to total carbon released to yield emissions of $CH_4$ and CO (each expressed in units of C). The emissions of $CH_4$ and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights. NMVOC could also be calculated in the same way. However, default values are not available in this edition of the *Guidelines*.

To calculate emissions of $N_2O$ and $NO_x$, first the carbon released is multiplied by the estimated ratio of nitrogen to carbon (N/C ratio) in savanna biomass by weight (0.006 is a general default value for savanna biomass burning (Crutzen and Andreae, 1990)). This yields the total amount of nitrogen (N) released from the biomass burned. The total N released is then multiplied by the ratios of emissions of $N_2O$ and $NO_x$ relative to the N released to yield emissions of $N_2O$ and $NO_x$ (expressed in units of N). To convert to full molecular weights, the emissions of $N_2O$ and $NO_x$ are multiplied by 44/28 and 46/14, respectively.[25]

The non-$CO_2$ trace gas emissions calculations from burning are summarised as follows:

$CH_4$ Emissions = (carbon released) x (emission ratio) x 16/12

CO Emissions = (carbon released) x (emission ratio) x 28/12

$N_2O$ Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 44/28

$NO_x$ Emissions = (carbon released) x (N/C ratio) x (emission ratio) x 46/14

TABLE 4-15
EMISSION RATIOS FOR SAVANNA BURNING CALCULATIONS

| Compound | Ratios | |
|---|---|---|
| $CH_4$ [a] | 0.004 | (0.002 - 0.006) |
| CO [b] | 0.06 | (0.04 - 0.08) |
| $N_2O$ [c] | 0.007 | (0.005 - 0.009) |
| $NO_x$ [c] | 0.121 | (0.094 - 0.148) |

Sources:
[a] Delmas, 1993
[b] Lacaux, et al., 1993
[c] Crutzen and Andreae, 1990

Note: Ratios for carbon compounds, i.e., $CH_4$ and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning (in units of C); those for the nitrogen compounds are expressed as the ratios of mass of nitrogen compounds released relative to the total mass of nitrogen released from the fuel.

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[24] This approach is adapted from Crutzen and Andreae, 1990, with some values updated, based on more recent studies by Delmas (1993), Delmas and Ahuja (1993) and Lacaux et al. (1993).

[25] The molecular weight ratios given above for the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for $N_2O$ the ratio is 44/28 and for $NO_X$ it is 46/14. $NO_2$ has been used as the reference molecule for $NO_X$.

## 4.4.3 Field Burning of Agricultural Residues

### Background

Large quantities of agricultural wastes are produced, from farming systems world-wide, in the form of crop residue.[26] Burning of crop residues, like the burning of savannas, is not thought to be a net source of carbon dioxide ($CO_2$) because the carbon released to the atmosphere during burning is reabsorbed during the next growing season. However, crop residue burning is a significant net source of $CH_4$, CO, $NO_x$, and $N_2O$. This section accounts for emissions of these non-$CO_2$ gases from field burning of agricultural crop residues. Burning of agricultural crop residues as an energy source is covered in the *Energy* chapter, in the section on fuel Combustion.

The amount of agricultural wastes produced varies by country, crop, and management system. For example, cereal crops produce between 0.6 and 2.5 tonnes of straw per tonne of grain (Barnard, 1990; Ponnamperuma, 1984), and wetland rice cultivated under a moderate level of management in the Philippines was found to produce between 0.6 and 0.9 tonnes of straw per tonne of grain (Ponnamperuma, 1984). Approximately 3.1 billion tonnes of crop residue are produced each year, with about 60 per cent originating in the developing world, and 40 per cent in the developed world (Strehler and Stützle, 1987).

Burning of agricultural wastes in the fields is a common practice in the developing world. It is used primarily to clear remaining straw and stubble after harvest and to prepare the field for the next cropping cycle. In Southeast Asia, burning is the major disposal method for rice straw (Ponnamperuma, 1984), which accounts for about 31 per cent of the agricultural waste in the developing world. Sugar cane residues, which make up about 11 per cent of the world's agricultural waste, are primarily disposed of by burning (Crutzen and Andreae, 1990). It has been estimated that as much as 40 per cent of the residues produced in developing countries may be burned in fields, while the percentage is lower in developed countries (Barnard and Kristoferson, 1985). Another study suggests that approximately 425 Tg dry matter agricultural wastes (~200 Tg C) are burned in the fields in developing countries and that about one-tenth as much is burned in developed countries (Crutzen and Andreae, 1990).

### Calculations

The methodology for estimating greenhouse gas emissions from burning of agricultural wastes is based, as in savanna burning, on 1) total carbon released, which is a function of the amount and efficiency of biomass burned and the carbon content of the biomass, and 2) the application of emission ratios of $CH_4$ and CO to total carbon released, and of $N_2O$ and $NO_x$ to total nitrogen released from biomass fires which are available from the scientific literature on biomass burning. It is generally recommended for all emissions from agriculture and land use change, that three-year averages of activity data (e.g., crop residues burned) be used if available.

### Step 1: Total Carbon Released from Burning Agricultural Residues

Data required, for each crop type, to calculate the amount of carbon burned in agricultural wastes are listed below:

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[26] Barnard (1990) outlines several broad categories of crop residue: woody crop residues (coconut shells, jute sticks, etc.), cereal residues (rice and wheat straw, maize stalks, etc.), green crop residues (groundnut straw, soybean tops, etc.), and crop processing residues (bagasse, rice husks, etc.).

- Amount of crops produced with residues that are commonly burned;
- Ratio of residue to crop product;
- Fraction of residue burned;
- Dry matter content of residue;
- Fraction oxidised in burning; and
- Carbon content of the residue.

There are standard default or literature values available for many of these data. Table 4-17 provides a summary of available default data. The most important data for users to provide are the actual amount of crops produced (by type) with residues that are commonly burned. Annual crop production statistics by country for most of the crops from which residues are burned are given in the *FAO Production Yearbooks, FAO (1991)*. Users may also find the *United Nations World Trade Yearbooks* useful. Crop-specific data for each country on ratios of residue to crop, fraction of residue burned, dry matter content of residue, and carbon content of residue can be incorporated at any time to replace the default values. A potentially valuable data source is the recent BUN/UNCED study by Professor D. Hall (and others) of Kings College, London, Hall et all (1994). In this context, one should also note the book *Renewable Energy: Sources for Fuels and Electricity* edited by Johansson et al. (1992).

From production data one can estimate the actual material (in carbon units) that is burned. One simple procedure is shown below:

Total carbon released (tonnes of carbon) =

$\sum_{\text{all crop types}}$ annual production (tonnes of biomass per year),

x the ratio of residue to crop product (fraction),

x the average dry matter fraction of residue (tonnes of dry matter / tonnes of biomass),

x the fraction actually burned in the field,

x the fraction oxidised,

x the carbon fraction (tonnes of carbon / tonnes of dry matter)

It is highly desirable to use country-specific data for these values wherever possible. Example estimates of residue/crop product ratios, average dry matter fraction and carbon fraction for certain crops are presented in Table 4-17.[27] If no other data are available,

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[27] Dry matter (dm), or dry biomass, refers to biomass in a dehydrated state. According to Elgin (1991), the moisture content of crop residue varies depending on the type of crop residue, climatic conditions (i.e., in a humid environment the residue will retain more moisture than in an arid environment), and the length of time between harvesting and burning of the residue. From a simple perspective, one can use the dry matter content values in Table 4-17 to convert from total crop residue to dry matter. For example, 200 tonnes of crop residue with a moisture content of 10%, would have a dry matter content of 90%, equal to 180 tonnes of dry matter. To convert from dry matter to carbon content, an average value of 0.45 t C/t dm can be used in the cases

the following assumptions regarding the fraction of crop residue burned in the field can be used as very crude default factors: for developing countries 0.25, and for developed countries a much smaller share possibly, 0.10 or less.[28] A default value of 0.90 for fraction oxidised can be used to account for the approximate 10 per cent of the carbon that remains on the ground as a result of charcoal formation and other aspects of incomplete combustion (Seiler and Crutzen, 1980; and Crutzen and Andreae, 1990).

### Step 2: Gas Emissions

Once the carbon released from field burning of agricultural residues has been estimated, the emissions of $CH_4$, CO, $N_2O$, and $NO_x$ can be calculated based on emission ratios (default values are provided in Table 4-16).[29] The amount of carbon released due to burning is multiplied by the emission ratios of $CH_4$ and CO relative to total carbon to yield emissions of $CH_4$ and CO (each expressed in units of C). The emissions of $CH_4$ and CO are multiplied by 16/12 and 28/12, respectively, to convert to full molecular weights. NMVOC could also be calculated in the same way. However, default values are not available in this edition of the *Guidelines*.

To calculate emissions of $N_2O$ and $NO_x$, first the total carbon released is multiplied by the estimated N-C ratio of the fuel by weight to yield the total amount of nitrogen (N) released. Some crop-specific values are given in Table 4-17 and 0.015 is a general default value for crop residues.[30] The total N released is then multiplied by the ratios of emissions of $N_2O$ and $NO_x$ relative to the N content of the fuel to yield emissions of $N_2O$ and $NO_x$ (expressed in units of N). To convert to full molecular weights, the emissions of $N_2O$ and $NO_x$ are multiplied by 44/28 and 46/14, respectively.[31]

The calculation for trace gas emissions from burning is summarised as follows:

$CH_4$ Emissions = Carbon Released x (emission ratio) x 16/12

CO Emissions = Carbon Released x (emission ratio) x 28/12

$N_2O$ Emissions = Carbon Released x (N/C ratio) x (emission ratio) x 44/28

$NO_x$ Emissions = Carbon Released x (N/C ratio) x (emission ratio) x 46/14

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where crop specific data are not available. The terms dry matter and dry biomass are used interchangeably in this text.

[28] Crutzen and Andreae, 1990. The estimates are very speculative and should be used with caution. The actual percentage burned varies substantially by country and crop type. This is an area where locally developed, country-specific data are highly desirable. As this issue is studied further, it may be possible to incorporate more accurate, country-and crop-specific percentages into future editions of the *Guidelines*.

[29] This approach is adapted from Crutzen and Andreae, 1990, with some values updated based on more recent studies by Delmas (1993), Delmas and Ahuja (1993) and Lacaux et al. (1993).

[30] Crop specific values are generally in the range of 0.01-0.02, from Crutzen and Andreae, 1990, so that 0.015 can be used as a generally representative value if no other information is available.

[31] The molecular weight ratios given above for the emitted gases are with respect to the weight of nitrogen in the molecule. Thus for $N_2O$ the ratio is 44/28 and for $NO_X$ it is 46/14. $NO_2$ has been used as the reference molecule for $NO_X$.

### TABLE 4-16
### EMISSION RATIOS FOR AGRICULTURAL RESIDUE BURNING CALCULATIONS

| Compound | Ratios |
|---|---|
| $CH_4$ [a] | 0.005 Range 0.003 - 0.007 |
| CO [b] | 0.06 Range 0.04 - 0.08 |
| $N_2O$ [c] | 0.007 Range 0.005 - 0.009 |
| $NO_x$ [c] | 0.121 Range 0.094 - 0.148 |

Sources:

[a] Delmas, 1993

[b] Lacaux, et al., 1993

[c] Crutzen and Andreae, 1990

Note: Ratios for carbon compounds, i.e., $CH_4$ and CO, are mass of carbon compound released (in units of C) relative to mass of total carbon released from burning (in units of C); those for the nitrogen compounds are expressed as the ratios of mass of nitrogen compounds relative to the total mass of nitrogen released from the fuel.

TABLE 4-17
SELECTED CROP RESIDUE STATISTICS

| Product | Residue/Crop Product | Dry Matter Fraction | Carbon Fraction (% dm) | Nitrogen-Carbon (N-C) Ratio |
|---|---|---|---|---|
| Wheat | 1.3 | 0.78-0.88 | 0.4853 | 0.012 |
| Barley | 1.2 | 0.78-0.88 | 0.4567 | |
| Maize | 1 | 0.30-0.50 | 0.4709 | 0.02 |
| Oats | 1.3 | | | |
| Rye | 1.6 | | | |
| Rice | 1.4 | 0.78-0.88 | 0.4144 | 0.014 |
| Millet | 1.4 | | | 0.016 |
| Sorghum | 1.4 | | | 0.02 |
| Pea | 1.5 | | | |
| Bean | 2.1 | | | |
| Soya | 2.1 | | | 0.05 |
| Potatoes | 0.4 | 0.30-0.60 | 0.4226 | |
| Feedbeet | 0.3 | 0.10-0.20 [a] | 0.4072[a] | |
| Sugarbeet | 0.2 | 0.10-0.20 [a] | 0.4072[a] | |
| Jerusalem artichoke | 0.8 | | | |
| Peanut | 1 | | | |

Sources: Strehler and Stützle, 1987
Sugarbeet data from Ryan and Openshaw, 1991
Nitrogen content from Barnard and Kristoferson, 1985
[a] These figures are for beet leaves.

### Possible refinements of the basic calculations

The basic calculations presented above address the immediate release of non-$CO_2$ trace gases when savannas or crops are burned. This is believed to be the most important effect of biomass burning on GHG emissions and the best characterised at present. However, there are other issues not treated in these calculations. The effect of past burning on current emissions is one such issue. The longer-term release or uptake of these gases following burning is an important research issue and may be included in future refinements of the calculations. In particular, grassland fires (savanna burning) may perturb the soils sufficiently to release additional $N_2O$ and $NO_x$. Little is known about the magnitude of this flux so these emissions are not included in the first application of the methodology. It is less likely that such delayed releases are significant after field burning of agricultural residues, but this may also require further study.

Long term changes in soil carbon are certainly possible as a result of agricultural practices. In the land use change and forestry chapter, there is a general default assumption that soil carbon is gradually lost from agricultural lands over many years after forests are cleared. In fact, depending on the specific agricultural and soil management practices (including burning) which are used, there may be a variety of effects on soil carbon. For example, repeated burning of savannas and crop residues in fields may cause an increase in the amount of carbon stored in the soil over time. This is an area which requires further research and may lead to more detailed emissions estimation methods in the future.

In addition, agricultural practices such as overgrazing, which degrade the productivity of grasslands or other agricultural lands, reduce the amount of aboveground biomass which regrows. These could be considered sources of gradual emissions of carbon dioxide. This situation is not included in the basic calculations, but could be included in more refined calculations. National experts should determine whether or not this is important for their country, and whether or not they are able to provide input data.

A similar long-term effect can be observed from savanna burning. If the savannas are burned too frequently, complete regrowth may not occur. In this situation, grasslands can degrade over time, resulting in long-term losses of both aboveground and soil carbon. If this condition is significant, national experts are encouraged to estimate the annual effect and explain the assumptions and data used.

Another possible refinement is to account for carbon that might be sequestered through the use of agricultural residues to make durable products (e.g., bricks, composite boards). The default assumption is that the carbon sequestered in such activities on an annual basis is small, and can be ignored in the calculations, that is, as long as the stocks of such products are not significantly increasing or decreasing over time, their effect on emissions/removals can be ignored. If national experts believe the effects may be significant, they are encouraged to estimate this carbon sink and document the assumptions and data used.

# 4.5 Greenhouse Gas Emissions from Agricultural Soils

## 4.5.1 Introduction

Agricultural soils may emit or remove nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), and/or methane ($CH_4$).

This section presents the method for calculating national emissions of $N_2O$ from agriculture soils. This $N_2O$ method is a significant revision of the 1995 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1995). Carbon dioxide emissions from soils are described in the Chapter on Land-use Change and Forestry.

For $N_2O$, the 1995 Methodology was evaluated and the present method includes more sources of $N_2O$ and more explicit information about emission factors. Three sources of $N_2O$ are distinguished in the methodology: (i) direct emissions from agricultural soils, (ii) direct soil emissions from animal production (including stable emissions to be reported under Manure Management (Section 4.2) ), and (iii) $N_2O$ emissions indirectly induced by agricultural activities. The methodology is an approach which requires only input data available from FAO databases. To retain consistency with the source categories defined in the *IPCC Guidelines* (1995), not all $N_2O$ emissions from these sources are reported here. Emissions from animal waste management systems (i.e., before manure is added to soils), and from manure used for fuel, are reported under Section 4.2 and Energy Chapter, respectively, whereas emissions from human sewage are reported in the Waste Chapter. However, the description of the N cycle which produces these $N_2O$ sources is included in Section 4.5.4 to provide the reader with a coherent picture of the N cycle as related to agricultural soils.

Anthropogenic input into agricultural systems include synthetic fertiliser, nitrogen from animal wastes, nitrogen from increased biological N-fixation, and nitrogen derived from cultivation of mineral and organic soils through enhanced organic matter mineralisation. Nitrous oxide may be produced and emitted directly in agricultural fields, animal confinements or pastoral systems or be transported from agricultural systems into ground and surface waters through surface runoff, nitrogen leaching, consumption by humans and introduction into sewage systems which transport the nitrogen ultimately into surface water. Ammonia and oxides of N ($NO_x$) are also emitted from agricultural systems and may be transported off-site and serve to fertilise other systems which leads to enhanced production of $N_2O$.

Agricultural systems are considered as being the same throughout the world and this methodology does not take into account different crops, soils and climates which are known to regulate $N_2O$ production. These factors are not considered because limited data are available to provide appropriate emission factors. Countries which have data to show that default data are inappropriate for their country should include a full explanation for the values used. The method also uses a linear extrapolation between $N_2O$ emissions and fertiliser nitrogen application and in the indirect emissions section does not account for the probable lag time between nitrogen input and ultimate production of $N_2O$ as a result of this nitrogen input into agricultural soils.

Using midpoint emission factors this current methodology and the FAO data (FAO, 1990a;b), global $N_2O$–N emissions for the year 1989 were estimated. Direct emissions from agricultural soils totalled 2.5 Tg N, direct emissions from grazing animals totalled 1.6 Tg N and indirect emissions resulting from agricultural nitrogen input into the atmosphere and aquatic systems totalled 1.9 Tg $N_2O$–N. These estimates show that each of the three components of agriculture considered contribute about the same amount of $N_2O$ to the global atmospheric budget. The $N_2O$ input to the atmosphere from agricultural production as a whole has apparently been underestimated by the previous IPCC methodology by at least 70 per cent.

## 4.5.2 Direct $N_2O$ Emissions from Agricultural Soils (Including Glasshouse Systems Farming and Excluding Effects of Grazing Animals)

Anthropogenic sources of $N_2O$ can be biogenic (e.g., enhanced $N_2O$ production by bacteria in fertilised fields) or abiogenic (e.g., formation during burning processes). Several studies indicate that anthropogenic sources are largely biogenic, with agriculture as a major contributor (Bouwman et al., 1995; Mosier et al., 1995a;b).

Biogenic production of $N_2O$ in the soil results primarily from the nitrification and denitrification processes. Simply defined, nitrification is the aerobic microbial oxidation of ammonium to nitrate and denitrification is the anaerobic microbial reduction of nitrate to dinitrogen gas. Nitrous oxide is a gaseous intermediate in the reaction sequences of both processes which leaks from microbial cells into the soil atmosphere. Major regulators of these processes are temperature, pH and soil moisture content.

In most agricultural soils, biogenic formation of $N_2O$ is enhanced by an increase in available mineral nitrogen, which in turn increases nitrification and denitrification rates. Addition of fertiliser N, therefore, directly results in extra $N_2O$ formation. Most studies on $N_2O$ emissions from agricultural soils investigate the difference in $N_2O$ production between fertilised and unfertilised fields. Emissions from unfertilised fields are considered background emissions. However, actual background emissions from agricultural soils may be higher than historic natural emissions as a result of enhanced mineralisation of soil organic matter. This is particularly observed in organic soils in both cold and warm climates over the globe (Bouwman and van der Hoek, 1991; Kroeze, 1994). Background emissions may also be lower than historic emissions due to depletion of soil organic matter (Groffman et al., 1993).

## OVERVIEW OF SOURCES

### Introduction

The following sources and sink of $N_2O$ can be distinguished.

- Synthetic fertilisers;
- Animal excreta nitrogen used as fertiliser;
- Biological nitrogen fixation;
- Crop residue and sewage sludge application;
- Glasshouse farming;
- Cultivation of high organic content soils;
- Soil sink for $N_2O$.

All of these $N_2O$ sources are included in the methodology, except for sewage sludge application and the soil sink for $N_2O$. These sources and sinks are not estimated because emissions are negligible or data are insufficient.

### Synthetic fertilisers

Synthetic fertilisers are an important source of $N_2O$. The amount of synthetic fertiliser nitrogen applied to agricultural fields world-wide is well documented in the FAO database (FAO Annual Fertiliser Yearbook). Studies on fertiliser-induced $N_2O$ emissions have been revised by Bouwman (1994,1995), Cole et al. (1995), Mosier (1994) and Mosier et al. (1995a;b). Conversion factors used by Cole et al. (1995) and Mosier et al. (1995b) are recommended. This recommendation is based on discussions conducted during the preparation of the Cole et al. (1995) document and from Bouwman (1994) who estimated that 0.0125 ± 0.01 of the applied nitrogen was directly emitted as $N_2O$ (see Table 4-18). This range encompasses more than 90 per cent of the published field emission values summarised in Bouwman (1994). Note that most of the information in Bouwman's summary is derived from field studies conducted in temperate regions of the world since few annual flux measurements have been made in tropical agricultural systems.

**TABLE 4-18**

**DEFAULT EMISSION FACTORS FOR DIRECT EMISSIONS OF $N_2O$**

| | |
|---|---|
| $EF_1$ (fraction of N-input, kg $N_2O$-N/kg N) | 0.0125 (0.0025-0.0225)[a] |
| $EF_2$ (kg $N_2O$-N/ha/yr) | 5 temperate and 10 tropical (2-15) [a] |

[a] Indicates range

### Animal excreta nitrogen used as fertiliser

Although the amount of nitrogen used as fertiliser from animal excreta is more uncertain than the amount of synthetic fertiliser used, estimates can be made, based on animal population and agricultural practices, as shown in Section 4.5.3 of this Chapter (Table B-1, Appendix B). To account for the loss of fertiliser from $NH_3$ volatilisation and emission of nitric oxide (NO) through nitrification after fertiliser is applied to fields, $NH_3$ volatilisation and NO emission factors are needed. Even though climate, soil, fertiliser placement and type, and other factors influence $NH_3$ volatilisation and $NO_x$ emissions, a default emission factor of 0.1 (kg $NH_3$–N + $NO_x$–N emitted/kg N applied) can be used for synthetic fertilisers and 0.2 (kg $NH_3$–N + $NO_x$–N emitted/kg N applied) for animal waste fertiliser (Table 4-19) (0.2 is used for animal waste because of the potentially larger $NH_3$ volatilisation; see Section 4.5.4). The amount of nitrogen from these sources available for conversion to $N_2O$ is therefore equal to 90 per cent of the synthetic fertiliser nitrogen applied and 80 per cent of the animal waste nitrogen applied (Schepers and Mosier, 1991).

### Biological nitrogen fixation

Although the amount of nitrogen fixed by biological nitrogen fixation in agricultural systems can be estimated, the $N_2O$ conversion coefficient is even less certain. Biological nitrogen fixation (BNF) supplies globally some 90 to 140 Tg N/yr to agricultural systems (Peoples et al., 1995). Although more verification of these figures is necessary, all indications are that BNF contributes more nitrogen for plant growth than the total amount of synthetic nitrogen fertilisers applied to crops each year (Danso, 1995). The *IPCC Guidelines* (1995) mention equal rates. On average, BNF supplies 50-60 per cent of the nitrogen harvested in grain legumes, 55-60 per cent of the nitrogen in nitrogen fixing trees and 70-80 per cent of the nitrogen accumulated by pasture legumes (Danso, 1995). Cultivation of grain legumes, however, often results in net soil nitrogen depletion.

In the tropics and subtropics, the use of Azolla (a genus of aquatic ferns which contains an $N_2$-fixing cyanobacterium) is widespread. Azolla fixes 20-25 kg N/ha (Kumarasinghe and Eskew, 1991) which is released upon decomposition. This nitrogen serves to fertilise an associated crop and eventually to stimulate $N_2O$ formation.

Galbally et al. (1992) and Bouwman and Sombroek (1990) indicate that legumes may contribute to $N_2O$ emission in a number of ways. Atmospheric $N_2$ fixed by legumes can be nitrified and denitrified in the same way as fertiliser N, thus providing a source of $N_2O$. Additionally, symbiotically living Rhizobia in root nodules are able to denitrify and produce $N_2O$ (O'Hara and Daniel, 1985). Galbally et al. (1992) suggest an emission rate of 4 kg N/ha/yr from improved pastures, and Duxbury et al. (1982) suggest that legumes can increase $N_2O$ emissions from pastures by a factor of 2 or 3. More recently Carran et al. (1995) found annual $N_2O$ emissions ranging from 0.5 to 5 kg $N_2O$–N depending upon the relative fertility of the sampling location. In old and young rye grass/clover pastures Muller (personal communication) observed $N_2O$ emissions of 0.7 and 0.3 kg N/ha/yr, respectively.

The absolute amount of nitrogen fixed by a crop is also very uncertain (Peoples et al., 1995.). Because of this uncertainty and the paucity of country data on N-fixing crops, it is difficult to assign a conversion factor for $N_2O$ emissions derived from nitrogen fixation. Total nitrogen input ($F_{BN}$, Equation 1) is estimated by assuming that total crop biomass is about twice the mass of edible crop (FAO, 1990b), and a certain nitrogen content of nitrogen fixing crop ($Frac_{NCRBF}$, Table 4-19). A residue/crop ratio of 1 is assumed. For specific crops, ratios can be obtained from Table 4-17. This crop production is defined in FAO crop data bases as pulses and soybeans. The N-fixation contribution does not include $N_2O$ produced in legume pastures. This $N_2O$ production is at least partially accounted for in emissions from pastures that are being grazed (Section 4.5.3). Australia and New Zealand, for example, contain large areas of pasture land that includes legumes as part of the pastoral system. Little data are available for other parts of the globe (Mosier et al., 1995b).

### Crop residue and Sewage sludge application

There is only limited information concerning re-utilisation of nitrogen from crop residues and nitrogen from sewage sludge applied to agricultural lands. Although the amount of nitrogen that recycles into agricultural fields through these mechanisms may add 25-100 Tg of N/yr of additional nitrogen into agricultural soils (mainly from crop residues) the amount converted to $N_2O$ is not known. To account for the $N_2O$ in the inventory budget the emission factor for fertilisers is used as default and the amount of nitrogen re-entering cropped fields through crop residues is calculated from the FAO crop production data. Because no appropriate estimates of sewage sludge nitrogen used as fertiliser were found, this nitrogen input is not discussed further (FAO, 1978-1981).

Nitrous oxide emissions associated with crop residue decomposition are calculated here by estimating the amount of nitrogen entering soils as crop residue ($F_{CR}$). The amount of nitrogen entering the crop residue pool is calculated from crop production data. Since FAO data that can be used for this purpose only represent the edible portion of the crop, these must be roughly doubled to estimate total crop biomass. We then can assume a nitrogen percentage ($Frac_{NCRBF}$ and $Frac_{NCR0}$; Table 4-19) to convert from kg dry biomass/yr to kg N/yr in crops. Some countries may have sufficient information to define the nitrogen content of crop biomass more precisely. As a default we suggest distinguishing between N-fixing crops (pulses and soybeans) and non-N-fixing crops.

Some of the crop residues is removed from the field as crop (approximately 45 per cent), and some may be burned (approximately 25 per cent of the remaining residue in developing countries), or fed to animals.

### Glasshouse farming

N-fertiliser application to glasshouse-grown crops are typically high and nitrogen not recovered in the crops is frequently low (Postma et al, 1994). The available data are limited in scope, but three sets of studies indicate that $N_2O$ emissions from glasshouse crops may be relatively small. Postma et al. (1994) quantified $NH_3$ and $N_2O$ emissions from glasshouse cultivation of lettuce on a sandbed and found that $NH_3$ emissions and $N_2O$ emitted directly or in drainage water totalled less than 0.01 kg N/kg of nitrogen applied. Daum (personal communication, 1995) measured $N_2O$ emissions from soil-less culture cucumbers and found that N-loss rates as $N_2O$ ranged between 0.004 and 0.009 kg N/kg of nitrogen input into the culture system. Pollaris (1994) measured $N_2O$ emission in a glasshouse cultivation of tomato and lettuce and found respectively 0.007 and 0.014 kg of each kg of applied nitrogen emitted as $N_2O$. The importance of another factor, $N_2O$ emission during steam disinfection of glasshouse soils, is uncertain. Postma (personal communication, 1995) found that 2-25 kg $N_2O$-N/ha were lost during 10-hours following soil steaming. The extent of glasshouses to which this practice is applied is not known. Overall, these data suggest that $N_2O$ emissions from glasshouse agriculture do not need to be included separately in $N_2O$ emission inventories but should be included only in the total fertiliser nitrogen consumed within each country. Emissions from glasshouse agriculture is, therefore, not discussed further.

### Cultivation of high organic content soils

Large $N_2O$ emissions occur as a result of cultivation of organic soils (Histosols) due to enhanced mineralisation of old, N-rich organic matter (Guthrie and Duxbury, 1978; Klemedtsson, personal communication, 1995). The rate of N-mineralisation is determined by the N-quality of the Histosol, management practices and climatic conditions. The range for enhanced emissions of $N_2O$ due to cultivation is estimated to be 2-15 kg $N_2O$-N/ha/yr of cultivated Histosol. Default emission values of 5 and 10 kg $N_2O$-N/ha/yr are suggested for temperate and boreal, and tropical regions, respectively (Table 4-18). If better country values are available they should be used.

### Soil sink for $N_2O$

Aerobic soils are typically sources for $N_2O$, but small uptake rates have been observed in isolated instances in dry soils (Duxbury and Mosier, 1993) and in wet grass pastures (Ryden, 1981; 1983). In a seasonally burned “cerrado’ in Brazil, Nobre (1994) observed occasional small but inconsistent consumption rates and concluded that this sink was very small in these soils. Anaerobic soils have a large potential for reducing $N_2O$ to $N_2$ (Erich et al., 1984), since the major product of denitrification in soils is usually $N_2$ rather than $N_2O$. However, no large, constant $N_2O$ uptake has been reported, and flooded rice fields (Parashar, 1991), for example, generally show very small emissions, depending upon the time of cropping season (Minami and Fukushi, 1984). Apparently slow rates of dissolution and transport of atmospheric $N_2O$ in wet or flooded soils prevent this process from being a significant regulator of atmospheric $N_2O$. Until additional information is available to indicate that soil uptake, in aerobic or flooded soils, is important, soil uptake of atmospheric $N_2O$ will not be included in the $N_2O$ budget for agricultural systems.

## METHODOLOGY FOR ESTIMATING DIRECT $N_2O$ EMISSIONS FROM AGRICULTURAL FIELDS.

The *Revised IPCC 1996 Methodology* for assessing direct $N_2O$ emissions from agricultural fields includes consideration of synthetic fertiliser ($F_{SN}$), nitrogen from animal waste ($F_{AW}$), enhanced $N_2O$ production due to biological N-fixation ($F_{BN}$), nitrogen from crop residue mineralisation ($F_{CR}$) and soil nitrogen mineralisation due to cultivation of Histosols ($F_{OS}$). For futher information see: Bouwman (1994, 1995); Mosier (1994); Mosier et al. (1995a;b).

In this estimate, the total direct annual $N_2O$ emission is:

**EQUATION 1**

$$N_2O_{DIRECT} = [(F_{SN} + F_{AW} + F_{BN} + F_{CR}) \times EF_1] + F_{OS} \times EF_2$$

where:

$N_2O_{DIRECT}$ = direct $N_2O$ emissions from agricultural soils in country (kg N/yr);

$EF_1$ = emission factor for direct soil emissions (kg $N_2O$-N/kg N input) (see Table 4-18);

$EF_2$ = emission factor for organic soil mineralisation due to cultivation (kg $N_2O$-N ha/yr) (see Table 4-18);

$F_{OS}$ = area of cultivated organic soils within country (ha of histosols in FAO data base);

$F_{AW}$ = manure nitrogen used as fertiliser in country, corrected for $NH_3$ and $NO_x$ emissions and excluding manure produced during grazing (kg N/yr);

$F_{BN}$ = N fixed by N-fixing crops in country (kg N/yr);

$F_{CR}$ = N in crop residues returned to soils in country (kg N/yr);

$F_{SN}$ = synthetic nitrogen applied in country (kg N/yr);

$F_{SN}$ = $N_{FERT} \times (1-Frac_{GASF})$;

$F_{AW}$ = $(Nex \times (1-(Frac_{FUEL} + Frac_{GRAZ} + Frac_{GASM}))$;

$F_{BN}$ = $2 \times Crop_{BF} \times Frac_{NCRBF}$;

$F_{CR}$ = $2 \times [Crop_0 \times Frac_{NCR0} + Crop_{BF} \times Frac_{NCRBF}] \times (1-Frac_R) \times (I-Frac_{BURN})$;

and

$N_{FERT}$ = synthetic fertiliser use in country (kg N/yr);

$Frac_{GASF}$ = fraction of synthetic fertiliser nitrogen applied to soils that volatilises as $NH_3$ and $NO_x$ (kg $NH_3$-N and $NO_x$-N/kg of N input) (see Table 4-19);

$N_{ex}$ = amount of nitrogen excreted by the livestock within a country (kg N/yr) (see Table 4-20);

$Frac_{FUEL}$ = fraction of livestock nitrogen excretion contained in excrements burned for fuel (kg N/kg N totally excreted)

$Frac_{GRAZ}$ = fraction of livestock nitrogen excreted and deposited onto soil during grazing (kg N/kg N excreted) country estimate;

$Frac_{GASM}$ = fraction of livestock nitrogen excretion that volatilises as $NH_3$ and $NO_x$ (kg $NH_3$-N and $NO_x$-N/kg of N excreted) (see Table 4-19);

$Crop_{BF}$ = seed yield of pulses + soybeans in country (kg dry biomass/yr);

$Frac_{NCRBF}$ = fraction of nitrogen in N-fixing crop (kg N/kg of dry biomass) (see Table 4-19);

$Crop_0$ = production of all other (i.e., non-N fixing) crops in country (kg dry biomass/yr);

$Frac_{NCR0}$ = fraction of nitrogen in non-N-fixing crop (kg N/kg of dry biomass) (see Table 4-19);

$Frac_R$ = fraction of crop residue that is removed from the field as crop (kg N/kg crop-N) (see Table 4-19);

$Frac_{BURN}$ = fraction of crop residue that is burned rather than left on field (see Table 4-19).

The input data needed for this methodology include synthetic fertiliser use ($N_{FERT}$), manure-N used as fertiliser ($F_{AW}$), edible crop production of N-fixing crops ($Crop_{BF}$) and non-N-fixing crops ($Crop_0$), and area of cultivated organic soils (Histosols) in the country. The data for synthetic fertiliser use are available on a country basis in the FAO data base (e.g., FAO, 1990a) and the amount of nitrogen in animal waste applied to agricultural fields ($F_{AW}$) is calculated from the number and type of animals within a country (see Section 4.5.3) and an in-country estimate of the percentage of nitrogen excreted by farm animals that is reapplied to the field. Both synthetic fertiliser and manure used as fertiliser need to be corrected for the amount of $NH_3$ volatilised and $NO_x$ emitted (10 and 20 per cent of nitrogen applied, respectively) after the material is placed in or on the soil so that the same nitrogen atom is not counted again in Section 4.5.4. The $F_{AW}$ data also need to be carefully evaluated for each country to be sure that animal waste used to fertilise crops and animal waste deposited on pastures while animals are grazing (accounted for in Section 4.5.3) are not double counted. Crop production data for pulses and soybeans and non-N-fixing crops are listed in the FAO crop data base (FAO, 1990b). Residue remaining on the field may not always total 55 per cent of total crop biomass. If more appropriate biomass and N content numbers are available within a country they should be used. The area of histosol can be obtained from FAO Databases (e.g., FAO, 1991).

**TABLE 4-19**
**DEFAULT VALUES FOR PARAMETERS**

| | |
|---|---|
| $Frac_{BURN}$ | 0.25 in developing and 0.10 or less in developed countries (kg N/kg crop-N); |
| $Frac_R$ | 0.45 kg N/kg crop-N; |
| $Frac_{FUEL}$ | 0.0 kg N/kg N excreted[a]; |
| $Frac_{GASF}$ | 0.1 kg $NH_3$-N + $NO_x$-N/kg of synthetic fertiliser N applied; |
| $Frac_{GASM}$ | 0.2 kg $NH_3$-N + $NO_x$-N/kg of N excreted by livestock; |
| $Frac_{GRAZ}$ | Table 4-21, Column Pasture range and Paddock [a]; |
| $Frac_{NCRBF}$ | 0.03 kg N/kg of dry biomass; |
| $Frac_{NCR0}$ | 0.015 kg N/kg of dry biomass. |

[a] Countries are recommended to obtain country specific data.

### 4.5.3 Direct soil emissions of $N_2O$ from animal production (including stable emissions to be reported under Manure Management)

#### OVERVIEW OF SOURCES

Recent studies (e.g., Bouwman, 1995; Jarvis and Pain, 1994; Flessa et al., submitted; Mosier et al., 1995a;b) indicate that emissions from animal wastes can be significant. There are three potential sources in animal production, (a) animals themselves, (b) animal wastes during storage and treatment, and (c) dung and urine deposited on the soil by grazing animals. Although $N_2O$ emissions from animals are described, they are not accounted for here as these are minor sources on a global scale and because such emissions are not a source of $N_2O$ emissions from soil. The second source includes possible losses during spreading operations. Emissions from manure stored in animal waste management systems (i.e., before it is added to soils), however, must be reported under Manure Management (Section 4.2). The final source, from grazing animals, is included in the agricultural soils because the dung and urine are considered as fertilisers.

#### A) $N_2O$ from animals

Animals themselves may be very small sources of $N_2O$. Animal fodders contain 10 to 40 g of nitrogen (N)/kg dry matter. The greater part of this nitrogen is organically bound, but as total nitrogen content increases so does the nitrate ($NO^-_3$) content, generally. Nitrate contents in fodders generally range from 1-10 g/kg dry matter (Spoelstra, 1985). Upon passage through the digestive track of the animal, nitrate is reduced via dissimilatory nitrate reduction to $NH_3/NH_4^+$. The nitrate reduction reaction may release small amounts of $N_2O$ in the gut (Kaspar and Tiedje, 1981), which may escape to the atmosphere during rumination. Though this possible route of $N_2O$ formation has been known for over 10 years, quantitative data in terms of $N_2O$ release are still lacking to-date. The total amount of $N_2O$ released by cattle is probably very small, because the gut is highly anoxic and this will favour the formation of $NH_3/NH_4^+$ (Tiedje, 1988). Direct losses from animals themselves are likely to be very small and are therefore not discussed further.

### B) $N_2O$ emissions from animal waste management systems

The proportion of total nitrogen intake that is excreted and partitioned between urine and faeces is dependent on the type of animal, the intake of dry matter, and the nitrogen concentration of the diet (Whitehead, 1970). The retention of nitrogen in animal products, i.e., milk, meat, wool and eggs, ranges from about 5 to 20 per cent of the total nitrogen intake, generally. The remainder is excreted via dung and urine. For sheep and cattle, faecal excretion is usually about 8g/N/kg dry matter consumed, regardless of the nitrogen content of the feed (Barrow and Lambourne, 1962). The remainder of the nitrogen is excreted in the urine and as the nitrogen content of the diet increases, so does the proportion of nitrogen in the urine. In animal production systems, where animal intake of nitrogen is high, more than half of the nitrogen is excreted as urine. For instance, sheep grazing grass/clover pastures in New Zealand have 70-75 per cent of excreted nitrogen in the urine (Haynes and Williams, 1993), whereas dairy cows in the Netherlands excrete 60-65 per cent of nitrogen in urine (Van Vuuren and Meijs, 1987).

There are small amounts of mineral nitrogen in faeces but the bulk of the nitrogen is in organic form. About 20-25 per cent of faecal nitrogen is water soluble, 15-25 per cent is undigested dietary nitrogen and the remaining 50-65 per cent is present in bacterial cells (Haynes and Williams, 1993). The organically bound nitrogen in faeces must be mineralised to $NH_3/NH_4^+$, before it can be the substrate of nitrifiers and denitrifiers and hence, a source of $N_2O$. Mineralisation of the water soluble organic nitrogen compounds and parts of the organic nitrogen compounds from bacterial cells is rapid, generally, leading to an increase in the amount of $NH_3/NH_4^+$ in animal wastes during storage.

The concentration of nitrogen in urine varies widely because of factors such as nitrogen content in the diet and consumption of water. Typically over 70 per cent of the nitrogen in urine is present as urea and the rest consists of amino acids and peptides. Excretions of poultry contains uric acid as dominant nitrogen compound. The hydrolysis of both urea and uric acid in urine patches to $NH_3/NH_4^+$ is very rapid, both in the pasture and in animal housings. Fresh urine and dung contain no nitrate; all nitrogen in wastes is in reduced forms.

Production of $N_2O$ during storage and treatment of animal wastes can occur via combined nitrification-denitrification of ammoniacal nitrogen contained in the wastes. The amount released depends on the system and duration of waste management. As fresh dung and slurry is highly anoxic and well-buffered with near neutral pH, one would expect $N_2O$ production to increase with increasing aeration. Aeration initiates the nitrification-denitrification reactions, and hence makes release of $N_2O$ possible. Unfortunately, there is not enough quantitative data to derive a relationship between the degree of aeration and $N_2O$ emission from slurry during storage and treatment.

Losses of $N_2O$ from cattle slurry during storing for up to 6 months, with two minutes of gentle mixing twice a week, were below detection limit ($10^{-4}$ kg $N_2O$ N/kg nitrogen in slurry during 6 months (Oenema and Velthof, 1993). $N_2O$ losses from a natural vented cubicle housing with 60 dairy cows and a concrete floor with frequent removal of wastes with a scarper system were also below the detection limit ($2.\ 10^{-4}$ kg N per kg nitrogen excreted) (Velthof et al., submitted a;b).

Heinemeyer (unpublished results) measured $N_2O$ losses from different housing systems for pigs. He obtained the following preliminary, results from the various housing systems: $6\ 10^{-4}$ -$11\ 10^{-4}$ kg $N_2O$-N/kg nitrogen excreted for full and half slit floor, and reduced and deep litter; $7.4\ 10^{-3}$ kg $N_2O$-N/kg nitrogen excreted for deep litter combined with compost; and $3.3\ 10^{-3}$ kg $N_2O$-N/kg nitrogen excreted for manure piles. The slightly larger losses from the deep litter/compost and manure pile could be due to the effects of aeration. Groenestein et al. (1993) reported that more than 0.15 kg N/kg nitrogen in pig