

## **CHAPTER 11**

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# **N<sub>2</sub>O EMISSIONS FROM MANAGED SOILS, AND CO<sub>2</sub> EMISSIONS FROM LIME AND UREA APPLICATION**

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# 11. N<sub>2</sub>O EMISSIONS FROM MANAGED SOILS, AND CO<sub>2</sub> EMISSIONS FROM LIME AND UREA APPLICATION

*Users are expected to go to Mapping Tables in Annex 1 Volume 4 (AFOLU), before reading this chapter. This is required to correctly understand both the refinements made and how the elements in this chapter relate to the corresponding chapter in the 2006 IPCC Guidelines.*

## 11.1 INTRODUCTION

No refinement.

## 11.2 NITROUS OXIDE (N<sub>2</sub>O) EMISSIONS FROM MANAGED SOILS

This section presents the methods and equations for estimating total national anthropogenic emissions of N<sub>2</sub>O (direct and indirect) from managed soils. The generic equations presented here can also be used for estimating N<sub>2</sub>O within specific land-use categories or by condition-specific variables (e.g., N additions to rice paddies) if the country can disaggregate the activity data to that level (i.e., N use activity within a specific land use).

Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N<sub>2</sub>). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil. This methodology, therefore, estimates N<sub>2</sub>O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilisers, deposited manure, crop residues, sewage sludge), or of mineralisation of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils (e.g., Forest Land/Grassland/Settlements converted to Cropland).

The emissions of N<sub>2</sub>O that result from anthropogenic N inputs or N mineralisation occur through both a direct pathway (i.e., directly from the soils to which the N is added/released), and through two indirect pathways: (i) following volatilisation of ammonia (NH<sub>3</sub>) and nitrogen oxides (NO<sub>x</sub>) from managed soils and from fossil fuel combustion and biomass burning, and the subsequent redeposition of these gases and their products NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> to soils and waters; and (ii) after leaching and runoff of N, mainly as NO<sub>3</sub><sup>-</sup>, from managed soils. The principal pathways are illustrated in Figure 11.1.

Direct emissions of N<sub>2</sub>O from managed soils are estimated separately from indirect emissions, though using a common set of activity data. The Tier 1 methodologies do not take into account different land cover, soil type, climatic conditions or management practices (other than specified below). Neither do they take account of any lag time for direct emissions from crop residue N, and allocate these emissions to the year in which the residues are returned to the soil. These factors are not considered for direct or (where appropriate, indirect) emissions because limited data are available to provide appropriate emission factors. Countries that have data to show that default factors are inappropriate for their country should utilise Tier 2 equations or Tier 3 approaches and include a full explanation for the values used.

### 11.2.1 Direct N<sub>2</sub>O emissions

In most soils, an increase in available N enhances nitrification and denitrification rates which then increase the production of N<sub>2</sub>O. Increases in available N can occur through human-induced N additions or change of land-use and/or management practices that mineralise soil organic N.

The following N sources are included in the methodology for estimating direct N<sub>2</sub>O emissions from managed soils:

- synthetic N fertilisers (F<sub>SN</sub>);
- organic N applied as fertiliser (e.g., animal manure, compost, sewage sludge, rendering waste, waste water effluent) (F<sub>ON</sub>);
- urine and dung N deposited on pasture, range and paddock by grazing animals (F<sub>PRP</sub>);

- N in crop residues (above-ground and below-ground), including from N-fixing crops <sup>1</sup> and from forages during pasture renewal <sup>2</sup> ( $F_{CR}$ );
- N mineralisation associated with loss of soil organic matter resulting from change of land use or management of mineral soils ( $F_{SOM}$ ); and
- Drainage/management of organic soils (i.e., Histosols) <sup>3</sup> ( $F_{OS}$ ).

### 11.2.1.1 CHOICE OF METHOD

The decision tree in Figure 11.2 provides guidance on which tier method to use.

#### Tier 1

In its most basic form, direct N<sub>2</sub>O emissions from managed soils are estimated using Equation 11.1 as follows:

**EQUATION 11.1**  
**DIRECT N<sub>2</sub>O EMISSIONS FROM MANAGED SOILS (TIER 1)**

$$N_2O_{Direct-N} = N_2O-N_{N_{inputs}} + N_2O-N_{OS} + N_2O-N_{PRP}$$

Where:

$$N_2O-N_{N_{inputs}} = \left[ \left[ (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \cdot EF_1 \right] + \left[ (F_{SN} + F_{ON} + F_{CR} + F_{SOM})_{FR} \cdot EF_{1FR} \right] \right]$$

$$N_2O-N_{OS} = \left[ (F_{OS,CG,Temp} \cdot EF_{2CG,Temp}) + (F_{OS,CG,Trop} \cdot EF_{2CG,Trop}) + (F_{OS,F,Temp,NR} \cdot EF_{2F,Temp,NR}) + (F_{OS,F,Temp,NP} \cdot EF_{2F,Temp,NP}) + (F_{OS,F,Trop} \cdot EF_{2F,Trop}) \right]$$

$$N_2O-N_{PRP} = \left[ (F_{PRP, CPP} \cdot EF_{3PRP, CPP}) + (F_{PRP, SO} \cdot EF_{3PRP, SO}) \right]$$

Where:

$N_2O_{Direct-N}$  = annual direct N<sub>2</sub>O–N emissions produced from managed soils, kg N<sub>2</sub>O–N yr<sup>-1</sup>

$N_2O-N_{N_{inputs}}$  = annual direct N<sub>2</sub>O–N emissions from N inputs to managed soils, kg N<sub>2</sub>O–N yr<sup>-1</sup>

$N_2O-N_{OS}$  = annual direct N<sub>2</sub>O–N emissions from managed organic soils, kg N<sub>2</sub>O–N yr<sup>-1</sup>

<sup>1</sup> Biological nitrogen fixation has been removed as a direct source of N<sub>2</sub>O because of the lack of evidence of significant emissions arising from the fixation process itself (Rochette and Janzen, 2005). These authors concluded that the N<sub>2</sub>O emissions induced by the growth of legume crops/forages may be estimated solely as a function of the above-ground and below-ground nitrogen inputs from crop/forage residue (the nitrogen residue from forages is only accounted for during pasture renewal). Conversely, the release of N by mineralisation of soil organic matter as a result of change of land use or management is now included as an additional source. These are significant adjustments to the methodology previously described in the *Revised 1996 IPCC Guidelines*. Countries may consider a Tier 2 approach for disaggregating low-N concentration crop residues from high-N concentration residues. Current knowledge shows no evidence for such a disaggregation at Tier 1 (Graham *et al.* 2017).

<sup>2</sup> The nitrogen residue from perennial forage crops is only accounted for during periodic pasture renewal, i.e. not necessarily on an annual basis as is the case with annual crops.

<sup>3</sup> Soils are organic if they satisfy the requirements 1 and 2, or 1 and 3 below (FAO, 1998): 1. Thickness of 10 cm or more. A horizon less than 20 cm thick must have 12 percent or more organic carbon when mixed to a depth of 20 cm; 2. If the soil is never saturated with water for more than a few days, and contains more than 20 percent (by weight) organic carbon (about 35 percent organic matter); 3. If the soil is subject to water saturation episodes and has either: (i) at least 12 percent (by weight) organic carbon (about 20 percent organic matter) if it has no clay; or (ii) at least 18 percent (by weight) organic carbon (about 30 percent organic matter) if it has 60 percent or more clay; or (iii) an intermediate, proportional amount of organic carbon for intermediate amounts of clay (FAO, 1998).

$N_2O-N_{PRP}$	= annual direct N <sub>2</sub> O–N emissions from urine and dung inputs to grazed soils, kg N <sub>2</sub> O–N yr <sup>-1</sup>
$F_{SN}$	= annual amount of synthetic fertiliser N applied to soils, kg N yr <sup>-1</sup>
$F_{ON}$	= annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (Note: If including sewage sludge, cross-check with Waste Sector to ensure there is no double counting of N <sub>2</sub> O emissions from the N in sewage sludge), kg N yr <sup>-1</sup>
$F_{CR}$	= annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N yr <sup>-1</sup>
$F_{SOM}$	= annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr <sup>-1</sup>
$F_{OS}$	= annual area of managed/drained organic soils, ha (Note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively)
$F_{PRP}$	= annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr <sup>-1</sup> (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)
$EF_1$	= emission factor for N <sub>2</sub> O emissions from N inputs, kg N <sub>2</sub> O–N (kg N input) <sup>-1</sup> (Table 11.1)
$EF_{1FR}$	= is the emission factor for N <sub>2</sub> O emissions from N inputs to flooded rice, kg N <sub>2</sub> O–N (kg N input) <sup>-1</sup> (Table 11.1) <sup>4</sup>
$EF_2$	= emission factor for N <sub>2</sub> O emissions from drained/managed organic soils, kg N <sub>2</sub> O–N ha <sup>-1</sup> yr <sup>-1</sup> ; (See guidance in <i>2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement)</i> , Chapter 2, Table 2.5 where further disaggregation by climate and land use is available) (Note: the subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively)
$EF_{3PRP}$	= emission factor for N <sub>2</sub> O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, kg N <sub>2</sub> O–N (kg N input) <sup>-1</sup> ; (Table 11.1) (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)

Conversion of N<sub>2</sub>O–N emissions to N<sub>2</sub>O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O-N * 44/28$$

## Tier 2

If more detailed emission factors and corresponding activity data are available to a country than are presented in Equation 11.1, further disaggregation of the terms in the equation can be undertaken. For example, if emission factors and activity data are available for the application of synthetic fertilisers and organic N ( $F_{SN}$  and  $F_{ON}$ ) under different conditions  $i$ , Equation 11.1 would be expanded to become <sup>5</sup>:

<sup>4</sup> When the total annual quantity of N applied to flooded paddy rice is known, this N input may be multiplied by a lower default emission factor applicable to this crop,  $EF_{1FR}$  (Table 11.1) or, where a country-specific emission factor has been determined, by that factor instead.

<sup>5</sup> It is important to note that Equation 11.2 is just one of many possible modifications to Equation 11.1 when using the Tier 2 method. The eventual form of Equation 11.2 will depend upon the availability of condition-specific emission factors and the ability to which a country can disaggregate its activity data.

**EQUATION 11.2****DIRECT N<sub>2</sub>O EMISSIONS FROM MANAGED SOILS (TIER 2)**

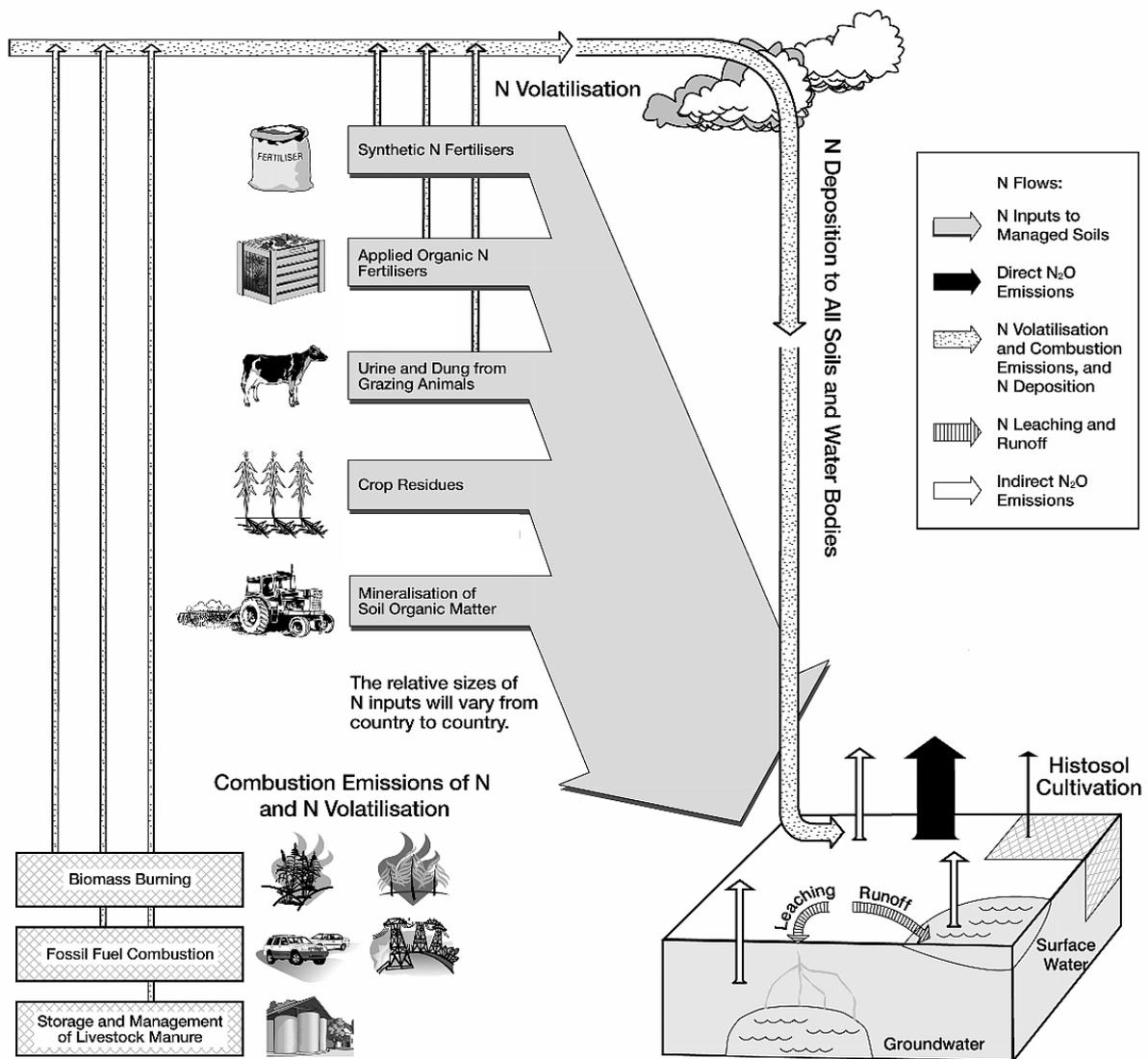
$$N_2O_{Direct-N} = \sum_i (F_{SN} + F_{ON})_i \cdot EF_{li} + (F_{CR} + F_{SOM}) \cdot EF_1 + N_2O-N_{OS} + N_2O-N_{PRP}$$

Where:

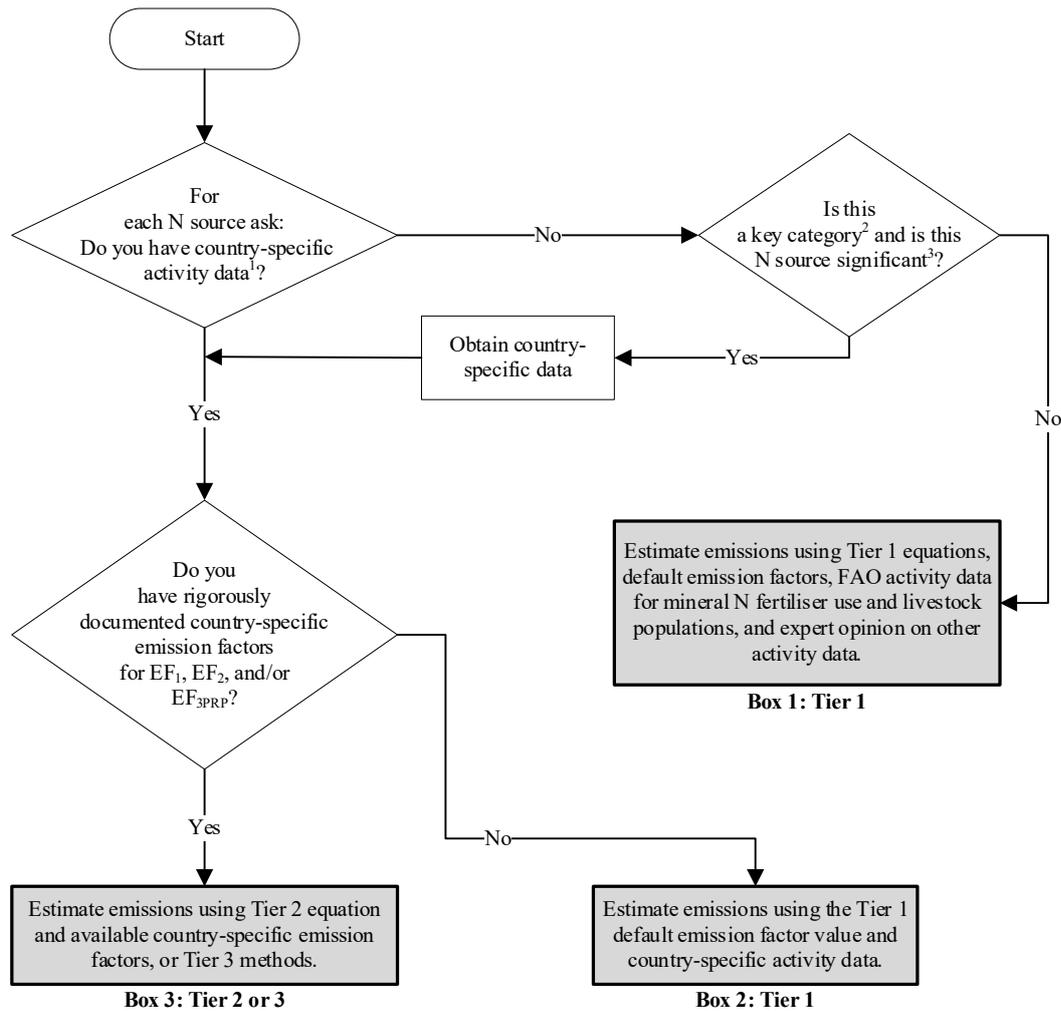
$EF_{li}$  = emission factors developed for N<sub>2</sub>O emissions from synthetic fertiliser and organic N application under conditions  $i$  (kg N<sub>2</sub>O-N (kg N input)<sup>-1</sup>);  $i = 1, \dots, n$

Equation 11.2 may be modified in a variety of ways to accommodate any combination of N source-, crop type-, management-, land use-, climate-, soil- or other condition-specific emission factors that a country may be able to obtain for each of the individual N input variables ( $F_{SN}$ ,  $F_{ON}$ ,  $F_{CR}$ ,  $F_{SOM}$ ,  $F_{OS}$ ,  $F_{PRP}$ ).

**Figure 11.1** Schematic diagram illustrating the sources and pathways of N that result in direct and indirect N<sub>2</sub>O emissions from soils and waters



Note: Sources of N applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows including the various pathways of volatilisation of NH<sub>3</sub> and NO<sub>x</sub> from agricultural and non-agricultural sources, deposition of these gases and their products NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>, and consequent indirect emissions of N<sub>2</sub>O are also illustrated. “Applied Organic N Fertilisers” include animal manure, all compost, sewage sludge, tankage, etc. “Crop Residues” include above- and below-ground residues for all crops (non-N and N fixing) and from perennial forage crops and pastures following renewal. On the lower right-hand side is a cut-away view of a representative sections of managed land; Histosol cultivation is represented here.

**Figure 11.2** Decision tree for direct N<sub>2</sub>O emissions from managed soils**Note**

1: N sources include: synthetic N fertiliser, organic N additions, urine and dung deposited during grazing, crop/forage residue, mineralisation of N contained in soil organic matter that accompanies C loss from soils following a change in land use or management and drainage/management of organic soils. Other organic N additions (e.g. compost, sewage sludge, rendering waste) can be included in this calculation if sufficient information is available. The waste input is measured in units of N and added as an additional source sub-term under  $F_{ON}$  in Equation 11.1 to be multiplied by  $EF_1$ .

2: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.

3: As a rule of thumb, a sub-category would be significant if it accounts for 25-30% of emissions from the source category.

Compilers can develop Tier 2 emission factors specific to mitigation options such as the application of nitrification inhibitors (Akiyama *et al.* 2010, Ruser & Schulz 2015, Gilsanz *et al.* 2016). Compilers can also consider an exponential response of N<sub>2</sub>O emissions to N application by developing country-specific emission factors (van Groenigen *et al.* 2010, Shcherbak *et al.* 2014, Gerber *et al.* 2016). This method will require activity data on specific fertiliser application rates to individual fields in order to apply rate-specific emission factors that capture the exponential response<sup>6</sup>. The influence of other environmental conditions, such as freeze-thaw cycles (Wagner-Riddle *et al.* 2017) can also be addressed with the development of Tier 2 emission factors.

Conversion of N<sub>2</sub>O–N emissions to N<sub>2</sub>O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O-N * 44/28$$

### Tier 3

Tier 3 methods are modelling or measurement approaches. Models are useful because in appropriate forms they can relate the soil and environmental variables responsible for N<sub>2</sub>O emissions to the size of those emissions. These relationships may then be used to predict emissions from whole countries or regions for which experimental measurements are impracticable. Models should only be used after validation by representative experimental measurements. Care should also be taken to ensure that the emission estimates developed through the use of models or measurements account for all anthropogenic N<sub>2</sub>O emissions<sup>7</sup>. Guidance that provides a sound scientific basis for the development of a Tier 3 Model-based system is given in Chapter 2, Section 2.5.

According to Equation 11.1, direct emissions of N<sub>2</sub>O from managed soils are calculated in the Tier 1 approach on the basis of total N applied to soils as synthetic and organic fertilisers and/or soil N mineralisation. The processes of run-off of N, volatilization of NH<sub>3</sub> and NO<sub>x</sub>, emissions of N<sub>2</sub>O, and leaching of N, however, do not occur simultaneously but in a sequence, with the peak of run-off and NH<sub>3</sub>+NO<sub>x</sub> volatilization happening before emissions of N<sub>2</sub>O and losses of N through leaching. For example, an application technique affecting the volatilization rate of NH<sub>3</sub>+NO<sub>x</sub> is likely to change the flow rates of subsequent processes. To illustrate, injecting slurry instead of broadcasting the organic amendment may increase the availability of N for N<sub>2</sub>O emissions and/or N-leaching, depending on climatic and soil conditions (Chadwick *et al.* 2011). It is therefore *good practice* to carefully assess such 'pollution swapping' effects when implementing a Tier 3 approach and adopting the N-flow principle when estimating direct N<sub>2</sub>O emissions. The same applies when estimating indirect N<sub>2</sub>O emissions from leaching and runoff (see Section 11.2.2.1). This adoption can be achieved by accounting for the decreased pool of nitrogen that is available for direct N<sub>2</sub>O emissions (and nitrogen leaching).

## 11.2.1.2 CHOICE OF EMISSION FACTORS

### Tiers 1 and 2

Three emission factors (EF) are needed to estimate direct N<sub>2</sub>O emissions from managed soils. The default values presented here may be used in the Tier 1 equation or in the Tier 2 equation in combination with country-specific emission factors. The first EF (EF<sub>1</sub>) refers to the amount of N<sub>2</sub>O emitted from the various synthetic and organic N applications to soils, including crop residue and mineralisation of soil organic carbon in mineral soils due to land-use change or management. The second EF (EF<sub>2</sub>) refers to the amount of N<sub>2</sub>O emitted from an area of drained/managed organic soils, and the third EF (EF<sub>3PRP</sub>) estimates the amount of N<sub>2</sub>O emitted from urine and dung N deposited by grazing animals on pasture, range and paddock. Default emission factors for the Tier 1 method are summarised in Table 11.1. For EF<sub>2</sub>, see guidance in *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Chapter 2, Table 2.5.

The default value for EF<sub>1</sub> has been set at 1 percent of the N applied to soils or released through activities that result in mineralisation of organic matter in mineral soils<sup>8</sup>. Given the growing number of studies highlighting the role

<sup>6</sup> The Tier 1 method is designed as a simple method for estimating direct N<sub>2</sub>O emissions with top-down commodity data on fertiliser production, import/export, or sales data. With these data, it is not possible to know the application rates to individual fields, which is needed for emission factors that are adjusted with application rates. However, variable emission factors can be developed with the Tier 2 method.

<sup>7</sup> Natural N<sub>2</sub>O emissions on managed land are assumed to be equal to emissions on unmanaged land. These latter emissions are very low. Therefore, nearly all emissions on managed land are considered anthropogenic. Estimates using the IPCC methodology are of the same magnitude as total measured emissions from managed land. Some Tier 3 methods may estimate only part of or aggregate some of the emission sources. Developers of Tier 3 methods should be aware of which components of Equation 11.2 are included in the estimate produced by their country-specific method.

<sup>8</sup> The value of EF<sub>1</sub> draws on a much larger number of measurements (see Annex 11A.2) than were available for the previous value used for EF<sub>1</sub> in the *2006 IPCC Guidelines* (Bouwman *et al.* 2002a,b; Novoa & Tejeda 2006; Stehfest & Bouwman 2006).

of climate and fertiliser type in determining EF<sub>1</sub> (Flechar *et al.* 2007, Aguilera *et al.* 2013, Cayuela *et al.* 2017), alternative emission factors that are disaggregated by climatic zone and fertiliser type are also provided. In wet climates, the default value has been set at 0.6 percent of organic N inputs and 1.6 percent of synthetic N inputs. In dry climates, the default value has been set at 0.5 percent of N inputs for both organic and synthetic N. These alternative factor values for EF<sub>1</sub> can be used by compilers that are able to disaggregate their activity data by climate<sup>9</sup> and fertiliser type. There are data to suggest that the emission factor could also be further disaggregated as part of a Tier 2 method. This disaggregation could be based on (1) environmental factors (soil organic C content, soil texture, drainage, soil pH and climate such as temperature and freeze-thaw cycle); and (2) management-related factors (N application rate per fertiliser type; fertiliser type, liquid or solid form of organic fertiliser; irrigation and type of crop with differences between legumes, non-leguminous arable crops, and grass) (e.g. Cayuela *et al.* 2017, Chadwick *et al.* 2018, Rochette *et al.* 2018, Wagner-Riddle *et al.* 2017).

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<sup>9</sup> Wet climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climate occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (cf. Figure 3A.5.1 in Chapter 3 of Vol. 4 provides a map subdividing wet and dry climates based on these criteria).

**TABLE 11.1 (UPDATED)**  
**DEFAULT EMISSION FACTORS TO ESTIMATE DIRECT N<sub>2</sub>O EMISSIONS FROM MANAGED SOILS**

Emission factor	Aggregated		Disaggregated		
	Default value	Uncertainty range	Disaggregation <sup>4</sup>	Default value	Uncertainty range
EF <sub>1</sub> for N additions from synthetic fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon <sup>1</sup> [kg N <sub>2</sub> O–N (kg N) <sup>-1</sup> ]	0.010	0.002 – 0.018	Synthetic fertiliser inputs <sup>5</sup> in wet climates	0.016	0.013 – 0.019
			Other N inputs <sup>6</sup> in wet climates	0.006	0.001 – 0.011
			All N inputs in dry climates	0.005	0.000 – 0.011
EF <sub>1FR</sub> for flooded rice fields <sup>2,7</sup> [kg N <sub>2</sub> O–N (kg N) <sup>-1</sup> ]	0.004	0.000 – 0.029	Continuous flooding	0.003	0.000 – 0.010
			Single and multiple drainage	0.005	0.000 – 0.016
EF <sub>3PRP, CPP</sub> for cattle (dairy, non-dairy and buffalo), poultry and pigs <sup>3</sup> [kg N <sub>2</sub> O–N (kg N) <sup>-1</sup> ]	0.004	0.000– 0.014	Wet climates	0.006	0.000 – 0.027
			Dry climates	0.002	0.000 – 0.007
EF <sub>3PRP, SO</sub> for sheep and ‘other animals’ <sup>3</sup> [kg N <sub>2</sub> O–N (kg N) <sup>-1</sup> ]	0.003	0.000 – 0.010	-	-	-

Sources:

<sup>1</sup> Stehfest & Bouwman 2006; van Lent *et al.* 2015; Grace *et al.* 2016; van der Weerden *et al.* 2016; Albanito *et al.* 2017; Cayuela *et al.* 2017; Liu *et al.* 2017; Rochette *et al.* 2018.

<sup>2</sup> Akiyama *et al.* 2005; Albanito *et al.* 2017; Cayuela *et al.* 2017.

<sup>3</sup> Yamulki *et al.* 1998; Galbally *et al.* 2000; Liebig *et al.* 2008; Cai & Akiyama 2016; Cardenas *et al.* 2016; Di *et al.* 2016; Hoogendoorn *et al.* 2016; Hyde *et al.* 2016; Krol *et al.* 2016; Li *et al.* 2016; Luo *et al.* 2016; Marsden *et al.* 2016; Misselbrook *et al.* 2016; Nichols *et al.* 2016; O’Connor *et al.* 2016; Owens *et al.* 2016; Pelster *et al.* 2016; Ward *et al.* 2016; Balvert *et al.* 2017; Byrnes *et al.* 2017; Forrestal *et al.* 2017; Marsden *et al.* 2017; Owens *et al.* 2017; Thomas *et al.* 2017a, b; Tully *et al.* 2017; van der Weerden *et al.* 2017; Cardoso *et al.* 2018; Chadwick *et al.* 2018; Nichols *et al.* 2018.

<sup>4</sup> Disaggregation of EF<sub>1</sub> and EF<sub>3PRP, CPP</sub> by climate (based on long-term averages): Wet climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (cf. Figure 3A.5.1 in Chapter 3 of Vol. 4 provides a map subdividing wet and dry climates based on these criteria). In wet climates, the EF<sub>1</sub> is further disaggregated by synthetic fertiliser N inputs and other N inputs.

<sup>5</sup> This emission factor should be used for synthetic fertiliser applications, and fertiliser mixtures that include both synthetic and organic forms of N.

<sup>6</sup> Other N input refers to organic amendments, animal manures (e.g. slurries, digested manures), N in crop residues and mineralised N from soil organic matter decomposition.

<sup>7</sup> Disaggregation of EF<sub>1FR</sub>: Single and multiple drainage also include alternate wetting and drying. Disaggregated EF<sub>1FR</sub> for rain-fed and deep-water systems not provided due to lack of data. The EF<sub>1</sub> should be used for upland rice.

Notes:

EF<sub>1</sub>: Uncertainty range of disaggregated EF<sub>1</sub> based on the 95% confidence interval of fitted values. Uncertainty range of aggregated EF<sub>1</sub> is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile of the dataset (See methods, data and results in Annex 11A.2).

EF<sub>1FR</sub>: Uncertainty range is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile (See methods and data in Annex 11A.3).

EF<sub>3PRP, CPP</sub> and EF<sub>3PRP, SO</sub>: Uncertainty range is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile (See methods and data in Annex 11A.4).

For EF<sub>2</sub>, see guidance in 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Chapter 2, Table 2.5.

Compilers that are able to disaggregate their activity data from all or some of these factors may choose to use disaggregated emission factors with the Tier 2 approach.

The default value for EF<sub>3PRP</sub> is 0.4 percent of the N deposited by all animal types except ‘sheep’ and ‘other’ animals. For these latter species, a default emission factor of 0.3 percent of the N deposited may be used<sup>10</sup>. EF<sub>3PRP</sub> for cattle,

<sup>10</sup> This is an update on the 2006 IPCC Guidelines, with over 400 cattle and sheep dung and urine EF<sub>3</sub> values collated from 13 countries (See Annex 11A.4). As noted in the 2006 IPCC Guidelines, reasons for the lower EF<sub>3PRP</sub> for sheep include more even urine distribution (smaller and more frequent urinations), and smaller effects on soil compaction during grazing. There are no or very limited data for N<sub>2</sub>O emission factors of other animal types, and the emission factor for poultry and swine is assumed to be the same as for cattle. However, a value of 0.3% of the nitrogen deposited may be used for animals classified as ‘other animals’ which includes goats, horses, mules, donkeys, camels, reindeer, and camelids, as these are likely to have

pigs and poultry (EF<sub>3PRP, CPP</sub>) is also disaggregated by wet and dry climates with values of 0.6 percent and 0.2 percent, respectively. There is no difference in EF<sub>3PRP</sub> for sheep and other animals (EF<sub>3PRP, SO</sub>) when disaggregated into wet and dry climates, therefore only an aggregated value is provided.

### 11.2.1.3 CHOICE OF ACTIVITY DATA

#### Tiers 1 and 2

This section describes generic methods for estimating the amount of various N inputs to soils (F<sub>SN</sub>, F<sub>ON</sub>, F<sub>PRP</sub>, F<sub>CR</sub>, F<sub>SOM</sub>, F<sub>OS</sub>) that are needed for the Tier 1 and Tier 2 methodologies (Equations 11.1 and 11.2).

#### Applied synthetic fertiliser (F<sub>SN</sub>)

The term F<sub>SN</sub> refers to the annual amount of synthetic N fertiliser applied to soils<sup>11</sup>. It is estimated from the total amount of synthetic fertiliser consumed annually. Annual fertiliser consumption data may be collected from official country statistics, often recorded as fertiliser sales and/or as domestic production and imports. If country-specific data are not available, data can be used from the International Fertilizer Association (IFA) (<http://www.fertilizer.org/ifa/statistics.asp>) on total fertiliser use by type and by crop, or from the Food and Agriculture Organisation of the United Nations (FAO) (<http://fao.org/faostat/>) on synthetic fertiliser consumption. It may be useful to compare national statistics to international databases such as those of the IFA and FAO. If sufficient data are available, fertiliser use may be disaggregated by fertiliser type, crop type and climatic regime for major crops. These data may be useful in developing revised emission estimates if inventory methods are improved in the future. It should be noted that most data sources (including FAO) might limit reporting to agricultural N uses, although applications may also occur on Forest Land, Settlements, or other lands. This unaccounted N is likely to account for a small proportion of the overall emissions. However, it is recommended that countries seek out this additional information whenever possible.

#### Applied organic N fertilisers (F<sub>ON</sub>)

The term “applied organic N fertiliser” (F<sub>ON</sub>) refers to the amount of organic N inputs (applied to soils other than by grazing animals) and is calculated using Equation 11.3. This includes applied animal manure, sewage sludge applied to soil, compost applied to soils, as well as other organic amendments of regional importance to agriculture (e.g., rendering waste, guano, brewery waste, etc.). Organic N fertiliser (F<sub>ON</sub>) is calculated using Equation 11.3:

**EQUATION 11.3**  
**N FROM ORGANIC N ADDITIONS APPLIED TO SOILS (TIER 1)**

$$F_{ON} = F_{AM} + F_{SEW} + F_{COMP} + F_{OOA}$$

Where:

- $F_{ON}$  = total annual amount of organic N fertiliser applied to soils other than by grazing animals, kg N yr<sup>-1</sup>
- $F_{AM}$  = annual amount of animal manure N applied to soils, kg N yr<sup>-1</sup>
- $F_{SEW}$  = annual amount of total sewage N (coordinate with Waste Sector to ensure that sewage N is not double-counted) that is applied to soils, kg N yr<sup>-1</sup>
- $F_{COMP}$  = annual amount of total compost N applied to soils (ensure that manure N in compost is not double-counted), kg N yr<sup>-1</sup>

nitrogen excretion rates and patterns that are more similar to sheep than to cattle. For disaggregation of EF<sub>3</sub> by dung and urine nitrogen for each livestock group, see Annex 11.4.

<sup>11</sup> For the Tier 1 approach, the amounts of applied mineral nitrogen fertilisers (F<sub>SN</sub>) and of applied organic nitrogen fertilisers (F<sub>ON</sub>) are no longer adjusted for the amounts of NH<sub>3</sub> and NO<sub>x</sub> volatilisation after application to soil. This is a change from the methodology described in the *Revised 1996 IPCC Guidelines*. The reason for this change is that field studies that have determined N<sub>2</sub>O emission factors for applied N were not adjusted for volatilisation when they were estimated. In other words, these emission factors were determined from: fertiliser-induced N<sub>2</sub>O–N emitted / total amount of N applied, and not from: fertiliser-induced N<sub>2</sub>O–N emitted / (total amount of N applied – NH<sub>3</sub> and NO<sub>x</sub> volatilised). As a result, adjusting the amount of N input for volatilisation before multiplying it with the emission factor would in fact underestimate total N<sub>2</sub>O emissions. Countries using Tier 2 or Tier 3 approaches should be aware that correction for NH<sub>3</sub>/NO<sub>x</sub> volatilisation after mineral or organic N application to soil may be required depending on the emission factor and/or the inventory methodology used.

$F_{OOA}$  = annual amount of other organic amendments used as fertiliser (e.g., rendering waste, guano, brewery waste, etc.), kg N yr<sup>-1</sup>

The term  $F_{AM}$  is determined by adjusting the amount of manure N available ( $N_{MMS\_Avb}$ ; see Equation 10.34 in Chapter 10) for the amount of managed manure used for feed ( $Frac_{FEED}$ ), burned for fuel ( $Frac_{FUEL}$ ), or used for construction ( $Frac_{CNST}$ ) as shown in Equation 11.4. Data for  $Frac_{FUEL}$ ,  $Frac_{FEED}$ ,  $Frac_{CNST}$  can be obtained from official statistics or a survey of experts. However, if these data are not available use  $N_{MMS\_Avb}$  as  $F_{AM}$  without adjusting for  $Frac_{FUEL}$ ,  $Frac_{FEED}$ ,  $Frac_{CNST}$ .

**EQUATION 11.4**  
**N FROM ANIMAL MANURE APPLIED TO SOILS (TIER 1)**

$$F_{AM} = N_{MMS\_Avb} \cdot \left[ 1 - \left( Frac_{FEED} + Frac_{FUEL} + Frac_{CNST} \right) \right]$$

Where:

$F_{AM}$  = annual amount of animal manure N applied to soils, kg N yr<sup>-1</sup>

$N_{MMS\_Avb}$  = amount of managed manure N available for soil application, feed, fuel or construction, kg N yr<sup>-1</sup> (see Equation 10.34 in Chapter 10)

$Frac_{FEED}$  = fraction of managed manure used for feed

$Frac_{FUEL}$  = fraction of managed manure used for fuel

$Frac_{CNST}$  = fraction of managed manure used for construction

*Urine and dung from grazing animals ( $F_{PRP}$ )*

The term  $F_{PRP}$  refers to the annual amount of N deposited on pasture, range and paddock soils by grazing animals. It is important to note that the N from managed animal manure applied to soils is included in the  $F_{AM}$  term of  $F_{ON}$ . The term  $F_{PRP}$  is estimated using Equation 11.5 from the number of animals in each livestock species/category  $T$  ( $N_{(T)}$ ), the annual average amount of N excreted by each livestock species/category  $T$  ( $Nex_{(T)}$ ), and the fraction of this N deposited on pasture, range and paddock soils by each livestock species/category  $T$  ( $MS_{(T,PRP)}$ ). The data needed for this equation can be obtained from the livestock chapter (see Chapter 10, Section 10.5).

Equation 11.5 provides an estimate of the amount of N deposited by grazing animals:

**EQUATION 11.5**  
**N IN URINE AND DUNG DEPOSITED BY GRAZING ANIMALS ON PASTURE, RANGE AND PADDOCK**  
**(TIER 1)**

$$F_{PRP} = \sum_T \left[ \left( N_{(T)} \cdot Nex_{(T)} \right) \cdot MS_{(T,PRP)} \right]$$

Where:

$F_{PRP}$  = annual amount of urine and dung N deposited on pasture, range, paddock by grazing animals, kg N yr<sup>-1</sup>

$N_{(T)}$  = number of head of livestock species/category  $T$  in the country (see Chapter 10, Section 10.2)

$Nex_{(T)}$  = annual average N excretion per head of species/category  $T$  in the country, kg N animal<sup>-1</sup> yr<sup>-1</sup> (see Chapter 10, Section 10.5)

$MS_{(T,PRP)}$  = fraction of total annual N excretion for each livestock species/category  $T$  that is deposited on pasture, range and paddock<sup>12</sup> (see Chapter 10, Section 10.5)

<sup>12</sup> In the livestock section, pasture, range and paddock is referred to as one of the manure management systems denoted as "S".

*Crop residue N, including N-fixing crops and forage/pasture renewal, returned to soils (F<sub>CR</sub>)*

The term F<sub>CR</sub> refers to the amount of N in crop residues (above-ground and below-ground), including N-fixing crops, returned to soils annually<sup>13</sup>. It also includes the N from N-fixing and non-N-fixing forages<sup>11,16</sup> mineralized during forage or pasture renewal<sup>14</sup>. It is estimated from crop yield statistics and default factors for above-/below-ground residue:yield ratios and residue N contents. In addition, the method accounts for the effect of residue burning or other removal of residues (direct emissions of N<sub>2</sub>O from residue burning are addressed under Chapter 2, Section 2.4). Because different crop types vary in residue:yield ratios, renewal time and N contents, separate calculations should be performed for major crop types and then N values from all crop types are summed up. At a minimum, it is recommended that crops be segregated into: 1) non-N-fixing grain crops (e.g., maize, rice, wheat, barley); 2) N-fixing grains and pulses (e.g., soybean, dry beans, chickpea, lentils); 3) root and tuber crops (e.g., potato, sweet potato, cassava); 4) N-fixing forage crops (alfalfa, clover); and 5) other forages including perennial grasses and grass/clover pastures. Equation 11.6 provides the equation to estimate N from crop residues and forage/pasture renewal, for a Tier 1 approach. As regards crop residue N, a cross check with the amount of N<sub>beddingMS</sub> of the Equation 10.34 “Managed manure N available for application to managed soils, feed, fuel or construction uses” (Volume 4, Chapter 10 Section 10.5.4) and biomass burning (Volume 4, Chapter 5 Section 5.2.4), relative to the amount of agricultural residues that is returned to soils other than the amount of agricultural residues that is removed for other purposes (e.g. bedding) or burnt should be done, in order to eliminate the possibility of double counting.

**EQUATION 11.6 (UPDATED)**  
**N FROM CROP RESIDUES AND FORAGE/PASTURE RENEWAL (TIER 1)**

$$F_{CR} = \sum_T \left\{ \left[ AGR_{(T)} \cdot N_{AG(T)} \cdot \left( 1 - \text{Frac}_{\text{Remove}(T)} - \left( \text{Frac}_{\text{Burnt}(T)} \cdot C_f \right) \right) \right] + \left[ BGR_{(T)} \cdot N_{BG(T)} \right] \right\}$$

$$AGR_{(T)} = AG_{DM(T)} \cdot \text{Area}_{(T)}$$

$$BGR_{(T)} = \left( \text{Crop}_{(T)} + AG_{DM(T)} \right) \cdot RS_{(T)} \cdot \text{Area}_{(T)} \cdot \text{Frac}_{\text{Renew}(T)}$$

$$AG_{DM(T)} = \text{Crop}_{(T)} \cdot R_{AG(T)}$$

Where:

- $F_{CR}$  = annual amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually, kg N yr<sup>-1</sup>
- $AGR_{(T)}$  = annual total amount of above-ground crop residue for crop  $T$ , kg d.m. yr<sup>-1</sup>.
- $N_{AG(T)}$  = N content of above-ground residues for crop  $T$ , kg N (kg d.m.)<sup>-1</sup> (Table 11.1a)
- $\text{Frac}_{\text{Remove}(T)}$  = fraction of above-ground residues of crop  $T$  removed annually for purposes such as feed, bedding and construction, dimensionless. Survey of experts in country is required to obtain data. If data for  $\text{Frac}_{\text{Remove}}$  are not available, assume no removal
- $\text{Frac}_{\text{Burnt}(T)}$  = fraction of annual harvested area of crop  $T$  burnt, dimensionless
- $C_f$  = combustion factor (dimensionless) (refer to Chapter 2, Table 2.6)
- $BGR_{(T)}$  = annual total amount of belowground crop residue for crop  $T$ , kg d.m. yr<sup>-1</sup>
- $N_{BG(T)}$  = N content of below-ground residues for crop  $T$ , kg N (kg d.m.)<sup>-1</sup>, (Table 11.1a)
- $AG_{DM(T)}$  = Above-ground residue dry matter for crop  $T$ , kg d.m. ha<sup>-1</sup>

<sup>13</sup> The equation to estimate F<sub>CR</sub> has been modified from the *Revised 1996 IPCC Guidelines* to account for the contribution of the below-ground nitrogen to the total input of nitrogen from crop residues, which previously was ignored in the estimate of F<sub>CR</sub>. As a result, F<sub>CR</sub> now represents a more accurate estimate of the amount of nitrogen input from crop residue, which makes it possible to assess the contribution to residue nitrogen arising from the growth of forage legumes such as alfalfa, where the harvesting of virtually all the above-ground dry matter results in no significant residue except the root system.

<sup>14</sup> The inclusion of nitrogen from forage or pasture renewal is a change from the *Revised 1996 IPCC Guidelines*.

(Use factors for  $R_{AG(T)}$  in Table 11.1a, or alternatively,  $AG_{DM(T)}$  may be estimated using the method and data in Table 11.2)

$Crop_{(T)}$	= harvested annual dry matter yield for crop $T$ , kg d.m. ha <sup>-1</sup>
$R_{AG(T)}$	= ratio of above-ground residue dry matter to harvested yield for crop $T$ ( $Crop_{(T)}$ ), kg d.m. ha <sup>-1</sup> (kg d.m. ha <sup>-1</sup> ) <sup>-1</sup> , (Table 11.1a)
$Area_{(T)}$	= total annual area harvested of crop $T$ , ha yr <sup>-1</sup>
$Frac_{Renew(T)}$	= fraction of total area under crop $T$ that is renewed annually <sup>15</sup> , dimensionless. For countries where pastures are renewed on average every $X$ years, $Frac_{Renew} = 1/X$ . For annual crops $Frac_{Renew} = 1$
$RS_{(T)}$	= ratio+ of below-ground root biomass to above-ground shoot biomass for crop $T$ , kg d.m. ha <sup>-1</sup> (kg d.m. ha <sup>-1</sup> ) <sup>-1</sup> , (Table 11.1a)
$T$	= crop or forage type

Data on crop yield statistics (yields and area harvested, by crop) may be obtained from national sources. If such data are not available, FAO publishes data on crop production: (<http://fao.org/faostat/>).

Since yield statistics for many crops are reported as field-dry or fresh weight, a correction factor should be applied to estimate dry matter yields ( $Crop_{(T)}$ ) where appropriate (Equation 11.7). The proper correction to be used is dependent on the standards that are applied for yield reporting, which may vary between countries. Alternatively, the default values for dry matter content given in Table 11.1a may be used.

**EQUATION 11.7**  
**DRY-WEIGHT CORRECTION OF REPORTED CROP YIELDS**

$$Crop_{(T)} = Yield\ Fresh_{(T)} \bullet DRY$$

Where:

$Crop_{(T)}$	= harvested dry matter yield for crop $T$ , kg d.m. ha <sup>-1</sup>
$Yield\ Fresh_{(T)}$	= harvested fresh yield for crop $T$ , kg fresh weight ha <sup>-1</sup>
$DRY$	= dry matter fraction of harvested crop $T$ , kg d.m. (kg fresh weight) <sup>-1</sup>

An improvement on this approach for determining  $F_{CR}$  (i.e., Tier 2) would be the use of country-specific data rather than the values provided in Table 11.1a, as well as country-specific values for the fraction of above-ground residue burned.

<sup>15</sup> This term is included in the equation to account for lower N release rates in grasslands that are not replanted annually (e.g., van der Weerden *et al.*, 1999; Davies *et al.*, 2001).

<b>TABLE 11.1A (NEW)</b> <b>DEFAULT VALUES FOR <math>N_{AG(T)}</math>, <math>N_{BG(T)}</math>, <math>R_{AG(T)}</math>, <math>RS_{(T)}</math> AND <math>DRY</math> TO BE USED IN EQUATIONS 11.6 AND 11.7</b>					
<b>Crops</b>	<b>N content of above-ground residues</b>  $(N_{AG(T)})^a$	<b>N content of below-ground residues</b>  $(N_{BG(T)})^a$	<b>Ratio of above-ground residue dry matter to harvested yield</b>  $(R_{AG(T)})^b$	<b>Ratio of below-ground biomass to above-ground biomass</b>  $(RS_{(T)})^a$	<b>Dry matter fraction of harvested product</b>  $(DRY)^a$
<b>Crops</b>					
Generic value for crops not indicated below <sup>c</sup>	0.008 (± 75%) <sup>d</sup>	0.009 (± 75%) <sup>d</sup>	1.0	0.22	0.85
Generic Grains	0.006 (± 75%) <sup>d</sup>	0.009 (± 75%) <sup>d</sup>	1.3	0.22 (±16%)	0.88
Winter Wheat	0.006 (± 75%) <sup>d</sup>	0.009 (± 75%) <sup>d</sup>	1.3	0.23 (±41%)	0.89
Spring Wheat	0.006 (± 75%) <sup>d</sup>	0.009 (± 75%) <sup>d</sup>	1.3	0.28 (±26%)	0.89
Barley	0.007 (± 75%) <sup>d</sup>	0.014 (± 75%) <sup>d</sup>	1.2	0.22 (± 33%)	0.89
Oats	0.007 (± 75%) <sup>d</sup>	0.008 (± 75%) <sup>d</sup>	1.3	0.25 (± 120%)	0.89
Maize	0.006 (± 75%) <sup>d</sup>	0.007 (± 75%) <sup>d</sup>	1.0	0.22 (± 26%)	0.87
Rye	0.005 (± 75%) <sup>d</sup>	0.011 (± 75%) <sup>d</sup>	1.6	- <sup>e</sup>	0.88
Rice	0.007 (± 75%) <sup>d</sup>	- <sup>e</sup>	1.4	0.16 (± 35%)	0.89
Millet	0.007 (± 75%) <sup>d</sup>	- <sup>e</sup>	1.4	- <sup>e</sup>	0.90
Sorghum	0.007 (± 75%) <sup>d</sup>	0.006 (± 75%) <sup>d</sup>	1.4	- <sup>e</sup>	0.89
Beans and Pulses	0.008 (± 75%) <sup>d</sup>	0.008 (± 75%) <sup>d</sup>	2.1	0.19 (± 45%)	0.91
Soybeans	0.008 (± 75%) <sup>d</sup>	0.008 (± 75%) <sup>d</sup>	2.1	0.19 (± 45%)	0.91
Potatoes and Tubers	0.019 (± 75%) <sup>d</sup>	0.014 (± 75%) <sup>d</sup>	0.4	0.20 (± 50%) <sup>f</sup>	0.22
Peanuts	0.016 (± 75%) <sup>d</sup>	- <sup>e</sup>	1.0	- <sup>e</sup>	0.94
Alfalfa	0.027 (± 75%) <sup>d</sup>	0.019 (± 75%) <sup>d</sup>	- <sup>e</sup>	0.40 (± 50%) <sup>g</sup>	0.90
Non-legume hay	0.015 (± 75%) <sup>d</sup>	0.012 (± 75%) <sup>d</sup>	- <sup>e</sup>	0.54 (± 50%) <sup>g</sup>	0.90
N-fixing forages	0.027 (± 75%) <sup>d</sup>	0.022 (± 75%) <sup>d</sup>	0.3	0.40 (± 50%)	0.90
Non-N-fixing forages	0.015 (± 75%) <sup>d</sup>	0.012 (± 75%) <sup>d</sup>	0.3	0.54 (± 50%)	0.90
Perennial Grasses	0.015 (± 75%) <sup>d</sup>	0.012 (± 75%) <sup>d</sup>	0.3	0.80 (± 50%) <sup>h</sup>	0.90
Grass-Clover Mixtures <sup>c</sup>	0.025 (± 75%) <sup>d</sup>	0.016 (± 75%) <sup>d</sup>	0.3	0.80 (± 50%) <sup>h</sup>	0.90
Sources:					
<sup>a</sup> Literature review by Stephen A. Williams, Natural Resource Ecology Laboratory, Colorado State University. A list of the original references is given in Annex 11A.1 of the 2006 IPCC Guidelines.					
<sup>b</sup> Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (GPG2000). Chapter 4 Table 4.16 for $R_{AG(T)}$ except forages, grasses and grass-clover mixes, which are from the 2006 IPCC Guidelines, Chapter 11, Table 11.2, and the generic value for all crops, which is the expert opinion of authors.					
Notes:					
<sup>c</sup> It is assumed here that grass dominates the system by 2 to 1 over legumes.					
<sup>d</sup> No uncertainty is provided in the original study. This uncertainty is expert-based judgment.					
<sup>e</sup> No estimate is available. The most appropriate generic value can be used based on expert judgment, in absence of more specific information available to develop a country-specific value.					
<sup>f</sup> This is an estimate of non-tuber roots based on the root:shoot values found for other crops. If unmarketable tuber yield is returned to the soil then data derived from Vangessel & Renner 1990 (see Annex 11A.1 of the 2006 IPCC Guidelines) (unmarketable yield = 0.08 * marketable yield = 0.29 * above-ground biomass) suggest that the total residues returned might then be on the order of 0.49 * above-ground biomass. Default s.d.					
<sup>g</sup> This is an estimate of root turnover in perennial systems. Default s.d.					
<sup>h</sup> Estimate of root turnover to above-ground production based on the assumption that in natural grass systems below-ground biomass is approximately equal to twice (one to three times) the above-ground biomass and that root turnover in these systems averages about 40% (30% to 50%) per year. Default s.d.					

**TABLE 11.2 (UPDATED)**  
**ALTERNATIVE METHOD AND DATA FOR ESTIMATING ABOVE-GROUND RESIDUE ( $AG_{DM(T)}$ )**

Crop	Above-ground residue dry matter $AG_{DM(T)}$ (kg d.m. ha <sup>-1</sup> ): $AG_{DM(T)} = Crop(T) \cdot Slope(T) + Intercept(T)$				
	$Slope(T)$	± 2 s.d. as % of mean	$Intercept(T)$	± 2 s.d. as % of mean	R <sup>2</sup> adj.
<i>Major crop types</i>					
Grains	1.09	± 2%	0.88	± 6%	0.65
Beans & pulses <sup>b</sup>	1.13	± 19%	0.85	± 56%	0.28
Tubers <sup>c</sup>	0.10	± 69%	1.06	± 70%	0.18
Root crops, other <sup>d</sup>	1.07	± 19%	1.54	± 41%	0.63
N-fixing forages	0.3	± 50% default	0	-	-
Non-N-fixing forages	0.3	± 50% default	0	-	-
Perennial grasses	0.3	± 50% default	0	-	-
Grass-clover mixtures	0.3	± 50% default	0	-	-
<i>Individual crops</i>					
Maize	1.03	± 3%	0.61	± 19%	0.76
Wheat	1.51	± 3%	0.52	± 17%	0.68
Winter wheat	1.61	± 3%	0.40	± 25%	0.67
Spring wheat	1.29	± 5%	0.75	± 26%	0.76
Rice	0.95	± 19%	2.46	± 41%	0.47
Barley	0.98	± 8%	0.59	± 41%	0.68
Oats	0.91	± 5%	0.89	± 8%	0.45
Millet	1.43	± 18%	0.14	± 308%	0.50
Sorghum	0.88	± 13%	1.33	± 27%	0.36
Rye <sup>e</sup>	1.09	± 50% default	0.88	± 50% default	-
Soybean <sup>f</sup>	0.93	± 31%	1.35	± 49%	0.16
Dry bean <sup>g</sup>	0.36	± 100%	0.68	± 47%	0.15
Potato <sup>h</sup>	0.10	± 69%	1.06	± 70%	0.18
Peanut (w/pod) <sup>i</sup>	1.07	± 19%	1.54	± 41%	0.63
Alfalfa	0.29 <sup>j</sup>	± 31%	0	-	-
Non-legume hay	0.18	± 50% default	0	-	-

## Sources:

<sup>a</sup> Literature review by Stephen A. Williams, Natural Resource Ecology Laboratory, Colorado State University. A list of the original references is given in Annex 11A.1 of the 2006 IPCC Guidelines.

## Notes:

<sup>b</sup> The average above-ground residue:grain ratio from all data used was 2.0 and included data for soya bean, dry bean, lentil, cowpea, black gram, and pea.

<sup>c</sup> Average of other crops.

<sup>d</sup> Modelled after peanuts.

<sup>e</sup> No data for rye. Slope and intercept values are those for all grain. Default s.d.

<sup>f</sup> The average above-ground residue:grain ratio from all data used was 1.9.

<sup>g</sup> Ortega, 1988 (see Annex 11A.1 of the 2006 IPCC Guidelines). The average above-ground residue:grain ratio from this single source was 1.6. default s.d. for root:AGB.

<sup>h</sup> The mean value for above-ground residue: tuber ratio in the sources used was 0.27 with a standard error of 0.04.

<sup>i</sup> The mean value for above-ground residue: pod yield in the sources used was 1.80 with a standard error of 0.10.

<sup>j</sup> This is the average above-ground biomass reported as litter or harvest losses. This does not include reported stubble, which averaged 0.165 \* Reported Yields. Default s.d.

*Mineralised N resulting from loss of soil organic C stocks in mineral soils through land-use change or management practices (F<sub>SOM</sub>)*<sup>16</sup>

The term F<sub>SOM</sub> refers to the amount of N mineralised from loss in soil organic C in mineral soils through land-use change or management practices. As explained in Chapter 2, Section 2.3.3, land-use change and a variety of management practices can have a significant impact on soil organic C storage. Organic C and N are intimately linked in soil organic matter. Where soil C is lost through oxidation as a result of land-use or management change, this loss will be accompanied by a simultaneous mineralisation of N. Where a loss of soil C occurs, this mineralised N is regarded as an additional source of N available for conversion to N<sub>2</sub>O (Smith and Conen, 2004); just as mineral N released from decomposition of crop residues, for example, becomes a source. The same default emission factor (EF<sub>1</sub>) is applied to mineralised N from soil organic matter loss as is used for direct emissions resulting from fertiliser and organic N inputs to agricultural land. This is because the ammonium and nitrate resulting from soil organic matter mineralisation is of equal value as a substrate for the microorganisms producing N<sub>2</sub>O by nitrification and denitrification, no matter whether the mineral N source is soil organic matter loss from land-use or management change, decomposition of crop residues, synthetic fertilisers or organic amendments. (Note: the opposite process to mineralisation, whereby inorganic N is sequestered into newly formed SOM, is not taken account of in the calculation of the mineralisation N source. This is because of the different dynamics of SOM decomposition and formation, and also because reduced tillage in some circumstances can increase both SOM and N<sub>2</sub>O emission).

For all situations where soil C losses occur (as calculated in Chapter 2, Equation 2.25) the Tier 1 and 2 methods for calculating the release of N by mineralisation are shown below:

*Calculation steps for estimating changes in N supply from mineralisation*

**Step 1:** Calculate the average annual loss of soil C ( $\Delta C_{\text{Mineral, LU}}$ ) for the area, over the inventory period, using Equation 2.25 in Chapter 2. Using the Tier 1 approach, the value for  $\Delta C_{\text{Mineral, LU}}$  will have a single value for all land-uses and management systems. Using Tier 2, the value for  $\Delta C_{\text{Mineral, LU}}$  will be disaggregated by individual land-use and/or management systems.

**Step 2:** Estimate the N mineralised as a consequence of this loss of soil C (F<sub>SOM</sub>), using Equation 11.8:

**EQUATION 11.8**

**N MINERALISED IN MINERAL SOILS AS A RESULT OF LOSS OF SOIL C THROUGH CHANGE IN LAND USE OR MANAGEMENT (TIERS 1 AND 2)**

$$F_{SOM} = \sum_{LU} \left[ \left( \Delta C_{\text{Mineral, LU}} \cdot \frac{1}{R} \right) \cdot 1000 \right]$$

Where:

$F_{SOM}$  = the net annual amount of N mineralised in mineral soils as a result of loss of soil carbon through change in land use or management, kg N

$\Delta C_{\text{Mineral, LU}}$  = average annual loss of soil carbon for each land-use type (LU), tonnes C (Note: for Approach 1 for land representation,  $\Delta C_{\text{Mineral, LU}}$  will have a single value for all land-uses and management systems. Using Approaches 2 and 3 for land representation the value for  $\Delta C_{\text{Mineral, LU}}$  will be disaggregated by individual land-use and/or management systems.

$R$  = C:N ratio of the soil organic matter. A default value of 15 (uncertainty range from 10 to 30) for the C:N ratio (R) may be used for situations involving land-use change from Forest Land or Grassland to Cropland, in the absence of more specific data for the area. A default value of 10 (range from 8 to 15) may be used for situations involving management changes on *Cropland Remaining Cropland*. C:N ratio can change over time, land use, or management practice<sup>17</sup>. If countries can document changes in C:N ratio, then different values can be used over the time series, land use, or management practice.

$LU$  = land-use and/or management system type

<sup>16</sup> The inclusion of the term F<sub>SOM</sub> is a change from the previous *Revised 1996 IPCC Guidelines*, which did not include the N from mineralisation associated with a loss of soil organic C.

<sup>17</sup> Information on C:N ratios in forest and cropped soils may be found in the following references: Aitkenhead-Peterson *et al.* 2005; Garten *et al.* 2000; John *et al.* 2005; Lobe *et al.* 2001; Snowdon *et al.* 2005, and other references cited by these authors.

**Step 3:** For Approach 1 for land representation, the value for  $F_{SOM}$  is calculated in a single step. For Approaches 2 and 3 for land representation,  $F_{SOM}$  is calculated by summing across all land-uses and/or management system types ( $LU$ ).

Countries that are not able to estimate gross changes of mineral soil C will create a bias in the N<sub>2</sub>O estimate, and it is *good practice* to acknowledge this limitation in the reporting documentation. It is also *good practice* to use specific data for the C:N ratios for the disaggregated land areas, if these are available, in conjunction with the data for carbon changes.

#### *Area of drained/managed organic soils ( $F_{OS}$ )*

The term  $F_{OS}$  refers to the total annual area (ha) of drained/managed organic soils (see footnote 3 for definition). This definition is applicable for both the Tier 1 and Tier 2 methods. For all land uses, the areas should be stratified by climate zone (temperate and tropical). In addition, for temperate Forest Land the areas should be further stratified by soil fertility (nutrient rich and nutrient poor). The area of drained/managed organic soils ( $F_{OS}$ ) may be collected from official national statistics. Alternatively, total areas of organic soils from each country are available from FAO (<http://fao.org/faostat/>), and expert judgement may be used to estimate areas that are drained/managed. For Forest Land, national data will be available at soil survey organisations and from wetland surveys, e.g., for international conventions. In case no stratification by soil fertility is possible, countries may rely on expert judgment.

### 11.2.1.4 UNCERTAINTY ASSESSMENT

No refinement.

## 11.2.2 Indirect N<sub>2</sub>O emissions

In addition to the direct emissions of N<sub>2</sub>O from managed soils that occur through a direct pathway (i.e., directly from the soils to which N is applied), emissions of N<sub>2</sub>O also take place through two indirect pathways (i.e., ‘off-site’ N<sub>2</sub>O emission from N volatilisation/deposition and N leaching, as illustrated above in Section 11.2).

The first of these pathways is the volatilisation of N as NH<sub>3</sub> and oxides of N (NO<sub>x</sub>), and the deposition of these gases and their products NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> onto soils and the surface of lakes and other waters. The sources of N as NH<sub>3</sub> and NO<sub>x</sub> are not confined to agricultural fertilisers and manures, but also include fossil fuel combustion, biomass burning, and processes in the chemical industry (see Volume 1, Chapter 7, Section 7.3). Thus, these processes cause N<sub>2</sub>O emissions in an exactly analogous way to those resulting from deposition of agriculturally derived NH<sub>3</sub> and NO<sub>x</sub>, following the application of synthetic and organic N fertilisers and /or urine and dung deposition from grazing animals. The second pathway is the leaching and runoff from land of N from synthetic and organic fertiliser additions, crop residues<sup>18</sup>, mineralisation of N associated with loss of soil C in mineral and drained/managed organic soils through land-use change or management practices, and urine and dung deposition from grazing animals. Some of the inorganic N in or on the soil, mainly in the NO<sub>3</sub><sup>-</sup> form, may bypass biological retention mechanisms in the soil/vegetation system by transport in overland water flow (runoff) and/or flow through soil macropores or pipe drains. Where NO<sub>3</sub><sup>-</sup> is present in the soil in excess of biological demand, e.g., under cattle urine patches, the excess leaches through the soil profile. The nitrification and denitrification processes described at the beginning of this chapter transform some of the NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> to N<sub>2</sub>O. This may take place in the groundwater below the land to which the N was applied, or in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers and estuaries (and their sediments) into which the land drainage water eventually flows.

This methodology described in this chapter addresses the following N sources of indirect N<sub>2</sub>O emissions from managed soils arising from agricultural inputs of N:

- synthetic N fertilisers ( $F_{SN}$ );
- organic N applied as fertiliser (e.g., applied animal manure<sup>19</sup>, compost, sewage sludge, rendering waste, waste water effluent and other organic amendments) ( $F_{ON}$ );
- urine and dung N deposited on pasture, range and paddock by grazing animals ( $F_{PRP}$ );

<sup>18</sup> Crop residues should be included as an N input into the leaching and runoff component.

<sup>19</sup> Volatilisation and subsequent deposition of nitrogen from the manure in manure management systems is covered in the manure management section of this volume.

- N in crop residues (above- and below-ground), including N-fixing crops and forage/pasture renewal returned to soils ( $F_{CR}$ )<sup>20</sup>; and
- N mineralisation associated with loss of soil organic matter resulting from change of land use or management on mineral soils ( $F_{SOM}$ ).

The generic Tier 1 and Tier 2 methods described below can be used to estimate aggregate total indirect N<sub>2</sub>O emissions from agricultural N additions to managed soils for an entire country. If a country is estimating its direct N<sub>2</sub>O from managed soils by land-use category, the indirect N<sub>2</sub>O emissions can also be estimated by the same disaggregation of land-use categories using the equations presented below with activity data, partitioning fractions, and/or emission factors specific for each land-use category. The methodology for estimating indirect N<sub>2</sub>O emissions from combustion-related and industrial sources is described in Volume 1, Chapter 7, Section 7.3.

### 11.2.2.1 CHOICE OF METHOD

Refer to the decision tree in Figure 11.3 (Indirect N<sub>2</sub>O Emissions) for guidance on which tier method to use.

#### Tier 1

*Volatilisation, N<sub>2</sub>O<sub>(ATD)</sub>*

The N<sub>2</sub>O emissions from atmospheric deposition of N volatilised from managed soil are estimated using Equation 11.9:

**EQUATION 11.9**  
**N<sub>2</sub>O FROM ATMOSPHERIC DEPOSITION OF N VOLATILISED FROM MANAGED SOILS (TIER 1)**

$$N_2O_{(ATD)-N} = \left[ (F_{SN} \cdot Frac_{GASF}) + ((F_{ON} + F_{PRP}) \cdot Frac_{GASM}) \right] \cdot EF_4$$

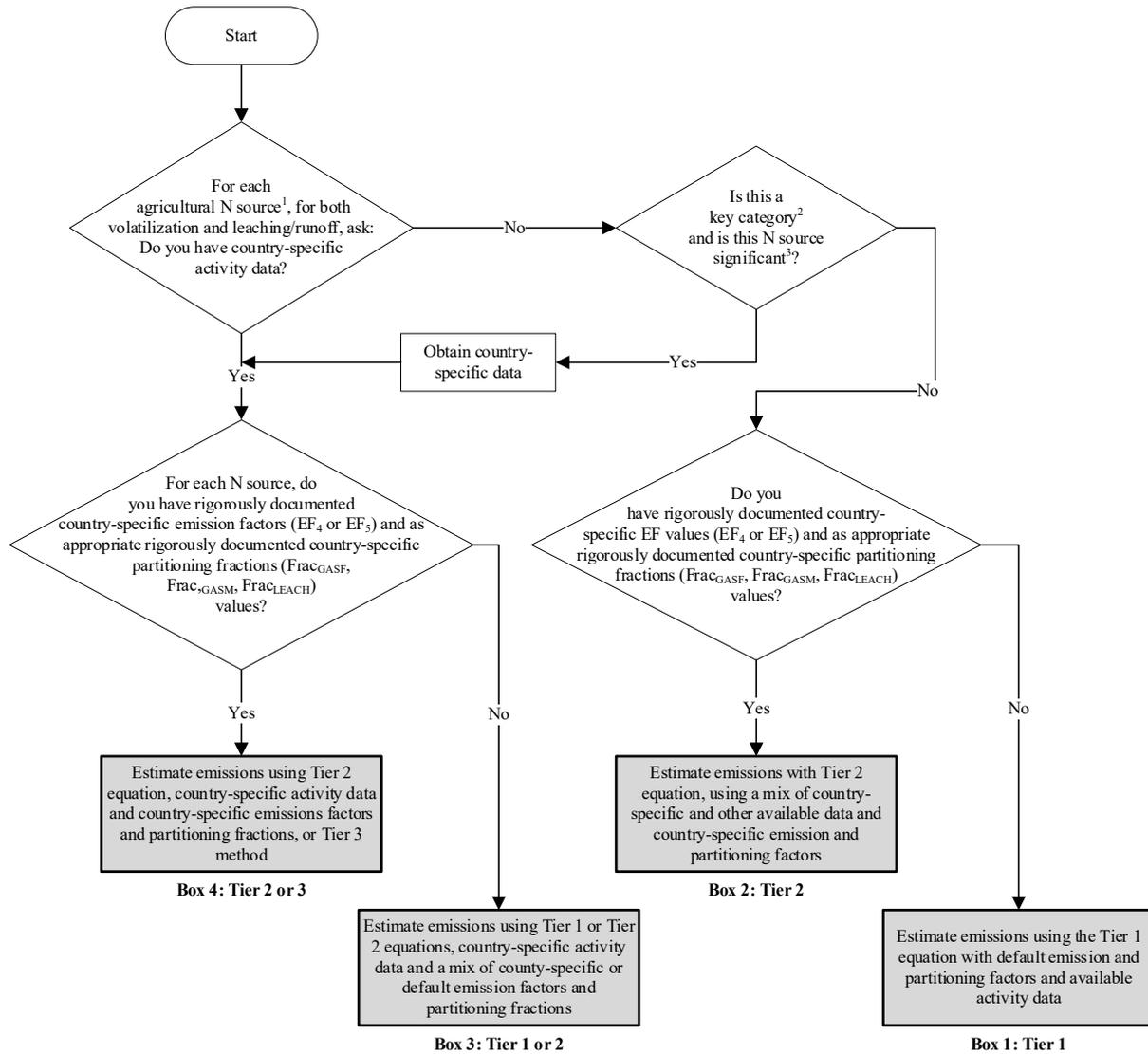
Where:

- $N_2O_{(ATD)-N}$  = annual amount of N<sub>2</sub>O–N produced from atmospheric deposition of N volatilised from managed soils, kg N<sub>2</sub>O–N yr<sup>-1</sup>
- $F_{SN}$  = annual amount of synthetic fertiliser N applied to soils, kg N yr<sup>-1</sup>
- $Frac_{GASF}$  = fraction of synthetic fertiliser N that volatilises as NH<sub>3</sub> and NO<sub>x</sub>, kg N volatilised (kg of N applied)<sup>-1</sup> (Table 11.3)
- $F_{ON}$  = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr<sup>-1</sup>
- $F_{PRP}$  = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr<sup>-1</sup>
- $Frac_{GASM}$  = fraction of applied organic N fertiliser materials ( $F_{ON}$ ) and of urine and dung N deposited by grazing animals ( $F_{PRP}$ ) that volatilises as NH<sub>3</sub> and NO<sub>x</sub>, kg N volatilised (kg of N applied or deposited)<sup>-1</sup> (Table 11.3)
- $EF_4$  = emission factor for N<sub>2</sub>O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N<sub>2</sub>O (kg NH<sub>3</sub>–N + NO<sub>x</sub>–N volatilised)<sup>-1</sup>] (Table 11.3)

Conversion of N<sub>2</sub>O<sub>(ATD)</sub>-N emissions to N<sub>2</sub>O emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(ATD)} = N_2O_{(ATD)-N} * 44/28$$

<sup>20</sup> Nitrogen from these components is only included in the leaching/run-off component of indirect N<sub>2</sub>O emission.

**Figure 11.3** Decision tree for indirect N<sub>2</sub>O emissions from managed soils

## Note

1: N sources include: synthetic N fertilizer, organic N additions, urine and dung depositions, crop residue, N mineralization/immobilization associated with loss/gain of soil C on mineral soils as a result of land use change or management practices (crop residue and N mineralization/immobilization is only accounted for in the indirect N<sub>2</sub>O emissions from leaching/runoff). Sewage sludge or other organic N additions can be included if sufficient information is available.

2: See Volume 1 Chapter 4, "Methodological Choice and Identification of Key Categories" (noting Section 4.1.2 on limited resources), for discussion of key categories and use of decision trees.

3: As a rule of thumb, a sub-source category would be significant if it accounts for 25-30% of emissions from the source category.

*Leaching/Runoff, N<sub>2</sub>O<sub>(L)</sub>*

The N<sub>2</sub>O emissions from leaching and runoff in regions where leaching and runoff occurs are estimated using Equation 11.10:

**EQUATION 11.10**  
**N<sub>2</sub>O FROM N LEACHING/RUNOFF FROM MANAGED SOILS IN REGIONS WHERE LEACHING/RUNOFF OCCURS (TIER 1)**

$$N_2O_{(L)}-N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \cdot Frac_{LEACH-(H)} \cdot EF_5$$

Where:

$N_2O_{(L)}-N$	= annual amount of N <sub>2</sub> O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N <sub>2</sub> O–N yr <sup>-1</sup>
$F_{SN}$	= annual amount of synthetic fertiliser N applied to soils in regions where leaching/runoff occurs, kg N yr <sup>-1</sup>
$F_{ON}$	= annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N yr <sup>-1</sup>
$F_{PRP}$	= annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs, kg N yr <sup>-1</sup> (from Equation 11.5)
$F_{CR}$	= amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, kg N yr <sup>-1</sup>
$F_{SOM}$	= annual amount of N mineralised in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, kg N yr <sup>-1</sup> (from Equation 11.8)
$Frac_{LEACH-(H)}$	= fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions) <sup>-1</sup> (Table 11.3)
$EF_5$	= emission factor for N <sub>2</sub> O emissions from N leaching and runoff, kg N <sub>2</sub> O–N (kg N leached and runoff) <sup>-1</sup> (Table 11.3)

Note: If a country is able to estimate the quantity of N mineralised from organic soils, then include this as an additional input to Equation 11.10.

Conversion of N<sub>2</sub>O<sub>(L)</sub>–N emissions to N<sub>2</sub>O emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(L)} = N_2O_{(L)}-N \bullet 44/28$$

## Tier 2

If more detailed emission, volatilisation or leaching factors are available to a country than are presented in Table 11.3, further disaggregation of the terms in the equations can also be undertaken. For example, if specific volatilisation factors are available for the application of synthetic fertilisers ( $F_{SN}$ ) under different conditions  $i$ , Equation 11.9 would be expanded to become <sup>21</sup>:

**EQUATION 11.11**  
**N<sub>2</sub>O FROM ATMOSPHERIC DEPOSITION OF N VOLATILISED FROM MANAGED SOILS (TIER 2)**

$$N_2O_{(ATD)}-N = \left\{ \sum_i (F_{SN_i} \bullet Frac_{GASF_i}) + [(F_{ON} + F_{PRP}) \bullet Frac_{GASM}] \right\} \bullet EF_4$$

Where:

$N_2O_{(ATD)}-N$	= annual amount of N <sub>2</sub> O–N produced from atmospheric deposition of N volatilised from managed soils, kg N <sub>2</sub> O–N yr <sup>-1</sup>
$F_{SN_i}$	= annual amount of synthetic fertiliser N applied to soils under different conditions $i$ , kg N yr <sup>-1</sup>
$Frac_{GASF_i}$	= fraction of synthetic fertiliser N that volatilises as NH <sub>3</sub> and NO <sub>x</sub> under different conditions $i$ , kg N volatilised (kg of N applied) <sup>-1</sup>

<sup>21</sup> It is important to note that Equation 11.11 is just one of many possible modifications to Equation 11.9, and is also meant to illustrate how Equation 11.10 could be modified, when using the Tier 2 method. The eventual form of Equation 11.11 will depend upon the availability of land use and/or condition-specific partitioning fractions and/or emission factors and the ability to which a country can disaggregate its activity data.

$F_{ON}$	= annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr <sup>-1</sup>
$F_{PRP}$	= annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr <sup>-1</sup>
$Frac_{GASM}$	= fraction of applied organic N fertiliser materials ( $F_{ON}$ ) and of urine and dung N deposited by grazing animals ( $F_{PRP}$ ) that volatilises as NH <sub>3</sub> and NO <sub>x</sub> , kg N volatilised (kg of N applied or deposited) <sup>-1</sup> (Table 11.3)
$EF_4$	= emission factor for N <sub>2</sub> O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N <sub>2</sub> O (kg NH <sub>3</sub> –N + NO <sub>x</sub> –N volatilised) <sup>-1</sup> ] (Table 11.3)

Countries can also develop emission factors for  $Frac_{GASF}$  and  $Frac_{GASM}$  that are specific for mitigation options such as the application of urease inhibitors.

Conversion of N<sub>2</sub>O<sub>(ATD)</sub>–N emissions to N<sub>2</sub>O<sub>(ATD)</sub> emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(ATD)} = N_2O_{(ATD)-N} \cdot 44 / 28$$

### Tier 3

Tier 3 methods are modelling or measurement approaches. Models are useful as they can relate the variables responsible for the emissions to the size of those emissions. These relationships may then be used to predict emissions from whole countries or regions for which experimental measurements are impracticable. For more information refer to Chapter 2, Section 2.5, where guidance is given that provides a sound scientific basis for the development of a Tier 3 Model-based system.

According to Equations 11.1, 11.9 and 11.10, direct and indirect emissions of N<sub>2</sub>O from managed soils are calculated in the Tier 1 approach on the basis of total N applied to soils as synthetic and organic fertilisers and/or soil N mineralisation. As noted in Section 11.2.1.1, the processes of run-off of N, volatilization of NH<sub>3</sub> and NO<sub>x</sub>, emissions of N<sub>2</sub>O, and leaching of N, however, do not occur simultaneously but in a sequence, with the peak of run-off and NH<sub>3</sub>+NO<sub>x</sub> volatilization happening before emissions of N<sub>2</sub>O and losses of N through leaching. Refer to Section 11.2.1.1 for *good practice* guidance when implementing a Tier 3 approach and adopting the N-flow principle when estimating direct N<sub>2</sub>O emissions and indirect N<sub>2</sub>O emissions from leaching and runoff.

## 11.2.2.2 CHOICE OF EMISSION, VOLATILISATION AND LEACHING FACTORS

The method for estimating indirect N<sub>2</sub>O emissions includes two emission factors: one associated with volatilised and re-deposited N ( $EF_4$ ), and the second associated with N lost through leaching/runoff ( $EF_5$ ). The method also requires values for the fractions of N that are lost through volatilisation ( $Frac_{GASF}$  and  $Frac_{GASM}$ ) or leaching/runoff ( $Frac_{LEACH-(H)}$ ). The default values of all these factors are presented in Table 11.3.

Note that in the Tier 1 method, for wet climates<sup>22</sup> or in dry climate regions where irrigation (other than drip irrigation) is used, the default  $Frac_{LEACH-(H)}$  is 0.24. For dry climates, the default  $Frac_{LEACH-(H)}$  is zero. The climate threshold for  $Frac_{LEACH-(H)}$  can be refined at Tier 2 by countries that are able to disaggregate their activity data (see methodological suggestion in Table 11.3).

Country-specific values for  $EF_4$  should be used with great caution because of the special complexity of transboundary atmospheric transport. Although inventory compilers may have specific measurements of N deposition and associated N<sub>2</sub>O flux, in many cases the deposited N may not have originated in their country. Similarly, some of the N that volatilises in their country may be transported to and deposited in another country, where different conditions that affect the fraction emitted as N<sub>2</sub>O may prevail. For these reasons the value of  $EF_4$  is very difficult to determine, and the method presented in Volume 1, Chapter 7, Section 7.3 attributes all indirect N<sub>2</sub>O emissions resulting from inputs to managed soils to the country of origin of the atmospheric NO<sub>x</sub> and NH<sub>3</sub>, rather than the country to which the atmospheric N may have been transported.

<sup>22</sup> Wet climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climate occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (cf. Figure 3A.5.1 in Chapter 3 of Vol. 4 provides a map subdividing wet and dry climates based on these criteria).

<b>TABLE 11.3 (UPDATED)</b>					
<b>DEFAULT EMISSION, VOLATILISATION AND LEACHING FACTORS FOR INDIRECT SOIL N<sub>2</sub>O EMISSIONS</b>					
Factor	Aggregated		Disaggregated		
	Default value	Uncertainty range	Disaggregation	Default value	Uncertainty range
EF <sub>4</sub> [N volatilisation and re-deposition] <sup>1</sup> , kg N <sub>2</sub> O–N (kg NH <sub>3</sub> –N + NO <sub>x</sub> –N volatilised) <sup>-1</sup>	0.010	0.002 - 0.018	Wet climate	0.014	0.011 – 0.017
			Dry climate	0.005	0.000 – 0.011
EF <sub>5</sub> [leaching/runoff] <sup>2</sup> , kg N <sub>2</sub> O–N (kg N leaching/runoff) <sup>-1</sup>	0.011	0.000 - 0.020	-	-	-
Frac <sub>GASF</sub> [Volatilisation from synthetic fertiliser] <sup>3</sup> , (kg NH <sub>3</sub> –N + NO <sub>x</sub> –N) (kg N applied) <sup>-1</sup>	0.11	0.02 - 0.33	Urea	0.15	0.03 – 0.43
			Ammonium-based	0.08	0.02 – 0.30
			Nitrate-based	0.01	0.00 – 0.02
			Ammonium-nitrate-based	0.05	0.00 – 0.20
Frac <sub>GASM</sub> [Volatilisation from all organic N fertilisers applied, and dung and urine deposited by grazing animals] <sup>4</sup> , (kg NH <sub>3</sub> –N + NO <sub>x</sub> –N) (kg N applied or deposited) <sup>-1</sup>	0.21	0.00 - 0.31	-	-	-
Frac <sub>LEACH-(H)</sub> [N losses by leaching/runoff in wet climates] <sup>5</sup> , kg N (kg N additions or deposition by grazing animals) <sup>-1</sup>	0.24	0.01 – 0.73	-	-	-

Sources:

<sup>1</sup> Stehfest & Bouwman 2006; van Lent *et al.* 2015; Grace *et al.* 2016; van der Weerden *et al.* 2016; Albanito *et al.* 2017; Cayuela *et al.* 2017; Liu *et al.* 2017; Rochette *et al.* 2018.

<sup>2</sup> Tian *et al.* 2019.

<sup>3</sup> NH<sub>3</sub>: Bouwman *et al.* 2002; Pan *et al.* 2016. NO<sub>x</sub>: Liu *et al.* 2017.

<sup>4</sup> NH<sub>3</sub>: Bouwman *et al.* 2002; Cai & Akiyama 2016. NO<sub>x</sub>: Liu *et al.* 2017.

<sup>5</sup> Reviews: Di & Cameron 2002; Cai & Akiyama 2016. Original papers: Moreno *et al.* 1996; Diez *et al.* 1997; Catt *et al.* 1998; Sogbedji *et al.* 2000; Asadi *et al.* 2002; Readman *et al.* 2002; Ren *et al.* 2003; Dauden & Quilez 2004; Dauden *et al.* 2004; Diez *et al.* 2004; Bakhsh *et al.* 2005; Basso & Ritchie 2005; Gehl *et al.* 2005; Fang *et al.* 2006; Li *et al.* 2006; Diez-Lopez *et al.* 2008; Conrad & Fohrer 2009; Zhu *et al.* 2009; Aronsson & Stenberg 2010; Bakhsh *et al.* 2010; Salmeron *et al.* 2010; Yague & Quilez 2010; Claret *et al.* 2011; Huang *et al.* 2011; Gallejones *et al.* 2012; Perego *et al.* 2012; Sorensen & Rubaek 2012; Tafteh & Sepaskhah 2012; Wang *et al.* 2012.

Notes:

Disaggregation by climate for EF<sub>4</sub> and Frac<sub>LEACH-(H)</sub> (based on long-term averages): Wet climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (cf. Figure 3A.5.1 in Chapter 3 of Vol. 4).

EF<sub>4</sub>: The aggregated EF<sub>4</sub> is the same as the aggregated EF<sub>1</sub> (see Annex 11A.5). The disaggregated EF<sub>4</sub> are the same as the EF<sub>1</sub> disaggregated by wet and dry climates (see Table A.2 in Annex 11A.2). Uncertainty range of the aggregated EF<sub>4</sub> is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile of the dataset, uncertainty range of disaggregated EF<sub>4</sub> is based on the 95% confidence interval of fitted values (See methods and data in Annex 11A.2).

EF<sub>5</sub>: This emission factor incorporates three components: EF<sub>5</sub> = EF<sub>5g</sub> + EF<sub>5r</sub> + EF<sub>5e</sub>. EF<sub>5g</sub>: Emission factor for groundwater and surface drainage, including upstream supersaturated with N<sub>2</sub>O (N<sub>2</sub>O emitted mainly from degassing of groundwater); EF<sub>5r</sub>: Emission factor for rivers and reservoirs, including downstream (supersaturated N<sub>2</sub>O was already degassed and N<sub>2</sub>O mainly produced by nitrification/denitrification in situ); EF<sub>5e</sub>: Emission factor for estuaries. See methods in Annex 11A.6. Uncertainty range is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile.

Frac<sub>GASF</sub>: Calculated by weighting world fertiliser usage with number of observations from review papers (See methods and data in Annex 11A.7). Uncertainty range based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile.

Frac<sub>GASM</sub>: See methods in Annex 11A.8. Uncertainty range is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile.

Frac<sub>LEACH-(H)</sub>: The Frac<sub>LEACH-(H)</sub> only applies to wet climates. For dry climate, the default Frac<sub>LEACH-(H)</sub> is taken as zero. See methods in Annex 11A.9. Uncertainty range is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile.

For Tier 2, country specific Frac<sub>LEACH-(H)</sub> can be estimated for N losses by leaching/runoff for regions where Σ(rain) - Σ(ET<sub>0</sub>) > soil water holding capacity, OR where irrigation (except drip irrigation) is used. ET<sub>0</sub> = Kpan \* Ep, where ET<sub>0</sub>: reference evapotranspiration, Kpan: pan evaporation coefficient, Ep: pan evaporation. When Kpan is not available, reference evaporation can be estimated as ET<sub>0</sub> = 0.5 \* Ep (Explanations of reference and pan evaporation: see Allen *et al.* 1998). Long-term mean of annual rainfall data should be used for estimating Frac<sub>LEACH-(H)</sub>. Precipitation and potential evapotranspiration data are available from global datasets, such as the CRU climate dataset (<https://crudata.uea.ac.uk/cru/data/hrg/>), if country-specific data are not available.

### 11.2.2.3 CHOICE OF ACTIVITY DATA

In order to estimate indirect N<sub>2</sub>O emissions from the various N additions to managed soils, the parameters F<sub>SN</sub>, F<sub>ON</sub>, F<sub>PRP</sub>, F<sub>CR</sub>, F<sub>SOM</sub> need to be estimated.

#### *Applied synthetic fertiliser (F<sub>SN</sub>)*

The term F<sub>SN</sub> refers to the annual amount of synthetic fertiliser N applied to soils. Refer to the activity data section on direct N<sub>2</sub>O emissions from managed soils (Section 11.2.1.3) and obtain the value for F<sub>SN</sub>.

#### *Applied organic N fertilisers (F<sub>ON</sub>)*

The term F<sub>ON</sub> refers to the amount of organic N fertiliser materials intentionally applied to soils. Refer to the activity data section on direct N<sub>2</sub>O emissions from managed soils (Section 11.2.1.3) and obtain the value for F<sub>ON</sub>.

#### *Urine and dung from grazing animals (F<sub>PRP</sub>)*

The term F<sub>PRP</sub> refers to the amount of N deposited on soil by animals grazing on pasture, range and paddock. Refer to the activity data section on direct N<sub>2</sub>O emissions from managed soils (Section 11.2.1.3) and obtain the value for F<sub>PRP</sub>.

#### *Crop residue N, including N from N-fixing crops and forage/pasture renewal, returned to soils (F<sub>CR</sub>)*

The term F<sub>CR</sub> refers to the amount of N in crop residues (above- and below-ground), including N-fixing crops, returned to soils annually. It also includes the N from N-fixing and non-N-fixing forages mineralised during forage/pasture renewal. Refer to the activity data section on direct N<sub>2</sub>O emissions from managed soils (Section 11.2.1.3) and obtain the value for F<sub>CR</sub>.

#### *Mineralised N resulting from loss of soil organic C stocks in mineral soils (F<sub>SOM</sub>)*

The term F<sub>SOM</sub> refers to the amount of N mineralised from the loss of soil organic C in mineral soils through land-use change or management practices. Refer to the activity data section on direct N<sub>2</sub>O emissions from managed soils (Section 11.2.1.3) and obtain the value for F<sub>SOM</sub>.

### 11.2.2.4 UNCERTAINTY ASSESSMENT

No refinement.

## 11.2.3 Completeness, Time series, QA/QC

No refinement.

## 11.3 CO<sub>2</sub> EMISSIONS FROM LIMING

No refinement.

## 11.4 CO<sub>2</sub> EMISSIONS FROM UREA FERTILIZATION

No refinement.

## **Annex 11A.1    References for crop residue data in Table 11.2**

No refinement.

## Annex 11A.2 Estimation of Default Emission Factor(s) for EF<sub>1</sub>

### Material and methods

We extracted all studies from the databases by Stehfest & Bouwman (2006), van Lent *et al.* (2015), Grace *et al.* (2016), van der Weerden *et al.* (2016), Albanito *et al.* (2017), Cayuela *et al.* (2017), Liu *et al.* (2017), and Rochette *et al.* (2018) and excluded studies which:

- Were non-peer-reviewed publications.
- Were conducted in the laboratory and greenhouse, and modelling studies (only field studies were selected).
- Were conducted in flooded rice fields (emissions from N inputs in flooded rice are estimated using the EF<sub>1FR</sub>).
- Related to grazed soils where urine and/or dung were applied (emissions from urine/dung inputs in grazed soils are estimated using the EF<sub>3PRP</sub>).
- Related to enhanced synthetic or organic fertiliser either treated with inhibitors or coated, and
- Were conducted on drained organic soils.

We further selected the cases from the source databases for which an emission factor had been or could be computed using a control site as:

$$EF_{1i} = \frac{N_2O_{Ti} - N_2O_{Ci}}{N_i}$$

Where N<sub>2</sub>O<sub>Ti</sub> is the N<sub>2</sub>O flux during the experimental period due to the application of inputs N<sub>i</sub> and other unquantified sources of N; and N<sub>2</sub>O<sub>Ci</sub> is the N<sub>2</sub>O flux during the experimental period at a control site due to other sources of N than N<sub>i</sub>.

Climate (Temperate/Boreal Wet, Temperate/Boreal, Dry Tropical Wet, Tropical Dry) was assigned to most cases. Temperate, boreal and tropical zones correspond to those defined in Chapter 3 of Vol. 4 in the 2006 IPCC Guidelines. Wet climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm. Climates were also grouped at a lower level of disaggregation by distinguishing dry climates from wet climates. Fertiliser was categorised as synthetic, organic or a mix of synthetic and organic forms. At a less disaggregated level, fertiliser comprised two groups: organic and synthetic plus mixed forms of fertiliser.

The linear mixed-effect model approach was selected for developing the disaggregated emission factors to account for lack of independence among data from individual sites compared to data from different sites. A location identification was assigned to all individual cases from experimental sites. Cases either with an identical coordinate or being from a same reference with a same soil type and a same land use were considered a unique location. The models included location identification as a random-effect, and climate, fertiliser or their interaction as fixed-effects. Influence of the length of the experiment, of the N application rate as well as influence of irrigation in dry climates was evaluated by considering these 3 variables as fixed-effects. The length of the experiment (days) was categorized into 5 classes as: ≤ 120, (120; 180], (180; 240], (240; 300], and > 300. The N application rate (kg N ha<sup>-1</sup> period<sup>-1</sup>) was categorized following the 6 classes: (0; 100], (100; 200], (200; 300], (300; 500], (500; 700], and > 700. Irrigation was categorized as “Yes” or “No”.

Means for the fixed-effects were compared using the LSD Fisher test to evaluate significant differences among the disaggregated EF<sub>1</sub> values, and only retain disaggregated values if significant. The confidence intervals for the predicted values from the linear mixed effect model was used to quantify uncertainty in the disaggregated EF<sub>1</sub>. The EF<sub>1</sub> was disaggregated by climate and fertiliser with no distinction between fertiliser form in dry climates (EF<sub>1</sub> Dry), but with a distinction between fertiliser form in wet climates (EF<sub>1</sub> Wet O and EF<sub>1</sub> Wet S + M) (see Results section and Table 11.1). Due to the imbalanced dataset between climates and fertiliser forms (76% in wet climate, 80% with synthetic plus mixed fertiliser form), the aggregated EF<sub>1</sub> could not be estimated using a linear mixed-effect model. Instead, a balanced distribution was derived with a bootstrapping method in which 1000 values were randomly selected from the distribution of each of the disaggregated EF<sub>1</sub> values (EF<sub>1</sub> Dry, EF<sub>1</sub> Wet O, EF<sub>1</sub> Wet S + M). The estimate for the aggregated EF<sub>1</sub> is the average from the resulting distribution and the confidence interval was derived based on the 2.5th to 97.5th percentile of the dataset (n = 3000).

### Results

The dataset was dominated by cases from Europe (34 percent) and North America (28 percent). Cases from Asia represented 19 percent of all cases while Africa, Central-South America, and Oceania formed an equal share of 6–7 percent of the dataset.

The linear mixed-effect model analysis indicated no clear trend of decrease or increase of the EF<sub>1</sub> according to the length of the experimental period or the N application rate (Table 2A.1). Therefore, these criteria were not considered further in the analysis.

<b>Disaggregation by length of experiment</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
≤120	335	0.012	0.008 – 0.015	B
(120, 180]	188	0.020	0.016 – 0.024	C
(180, 240]	84	0.009	0.003 – 0.014	B
(240, 300]	40	-0.002	-0.010 – 0.007	A
> 300	205	0.013	0.008 – 0.017	B
<b>Disaggregation by N application rate</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
(0, 100]	255	0.015	0.011 – 0.018	A
(100, 200]	377	0.011	0.007 – 0.014	A
(200, 300]	135	0.014	0.004 – 0.025	A
(300, 500]	63	0.010	0.004 – 0.015	A
(500, 700]	15	0.008	-0.002 – 0.018	A
> 700	11	0.013	0.009 – 0.017	A

The analysis yielded no significant difference in EF<sub>1</sub> between the four climates as disaggregated by temperature and rainfall (Table 2A.2). Disaggregation by rainfall pointed towards an EF<sub>1</sub> significantly higher in wet climate than in dry climate. In dry climate, irrigation led to a higher EF<sub>1</sub> than when irrigation was not practiced. Irrigation was practiced in most (63 percent) cases from dry climates, explaining the similarity between the EF<sub>1</sub> for dry climates and the EF<sub>1</sub> for irrigated fields in dry climates. Lower EF<sub>1</sub> for non-irrigated fields in dry climates may be used at Tier 2 level by compilers that have the corresponding activity data.

Comparison between the three fertiliser forms (S: Synthetic, O: Organic, M: Mixed S+O) suggested that synthetic and mixes of synthetic and organic forms could be grouped into a single category, while the EF<sub>1</sub> for organic fertiliser forms was significantly lower than the EF<sub>1</sub> for synthetic fertilisers. The EF<sub>1</sub> obtained from the interaction of climate disaggregated by rainfall and fertiliser with two levels of disaggregation (O and S + M) were similar in dry climates. In wet climates, the EF<sub>1</sub> of the S + M form was significantly higher than the EF<sub>1</sub> for the organic form.

Based on these results, the EF<sub>1</sub> was disaggregated by climate and fertiliser with no distinction between fertiliser form in dry climates (EF<sub>1 Dry</sub> = 0.5 percent), but with a distinction between organic fertiliser (EF<sub>1 Wet O</sub> = 0.6 percent) and synthetic plus mixed fertiliser (EF<sub>1 Wet S+M</sub> = 1.6 percent) in wet climates. The aggregated EF<sub>1</sub> computed from these disaggregated values amounted to 1.0 percent with an uncertainty range of 0.2 – 1.8 percent.

<b>Disaggregation by climate (temperature, rainfall)</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
Temperate/boreal wet	526	0.013	0.007 – 0.019	A B
Temperate/boreal dry	121	0.007	-0.002 – 0.015	A B
Tropical wet	122	0.014	0.011 – 0.018	B
Tropical dry	86	0.004	-0.004 – 0.013	A
<b>Disaggregation by rainfall</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
Wet	648	0.014	0.011 – 0.017	B
Dry	207	0.005	0.000 – 0.011	A
<b>Disaggregation by irrigation in dry climate</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
Irrigation	94	0.004	0.003 – 0.006	B
No irrigation	56	0.001	-0.001 – 0.003	A
<b>Disaggregation by fertiliser form (S: Synthetic, O: Organic, M: Mixed S+O) in wet climate</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
S	607	0.013	0.007 – 0.019	B
M	49	0.014	0.011 – 0.017	A B
O	163	0.007	0.003 – 0.011	A
<b>Disaggregation by climate (rainfall) and fertiliser form (S + M: Synthetic and Mixed S+O, O: Organic)</b>	<b>n</b>	<b>Mean</b>	<b>Uncertainty range</b>	<b>Significance</b>
Wet S + M	509	0.016	0.013 – 0.019	B
Wet O	110	0.006	0.001 – 0.011	A
Dry S + M	147	0.005	-0.003 – 0.013	A
Dry O	53	0.005	-0.003 – 0.013	A

### **Annex 11A.3 Estimation of Default Emission Factor(s) for EF<sub>1FR</sub>**

We extracted all studies with paddy rice field experiments that had a zero-N control from the databases by Akiyama *et al.* (2005), Albanito *et al.* (2017) and Cayuela *et al.* (2017). We excluded studies which:

- Were non-peer-reviewed publications;
- Were conducted in the laboratory and greenhouses, and modelling studies (only field studies were selected);
- Were conducted in upland rice fields;
- Were less than 70 days in duration;
- Related to grazed soils where urine and/or dung was applied; and
- Related to manure or fertilizer treated with inhibitors.

The database contained 70 EF<sub>1FR</sub> values and the arithmetic mean was 0.4 percent. Water management strongly affects N<sub>2</sub>O emission from paddy rice fields (Akiyama *et al.* 2005). Therefore, aggregated and disaggregated values by water management were calculated based on arithmetic means and confidence intervals were constructed to include 95 percent of the distribution of measured emissions. Arithmetic mean of ‘continuous flooding’ (0.3 percent, n = 44) was lower than ‘with single and multiple drainage’ (0.5 percent, n = 26). Only ‘continuous flooding and ‘with single and multiple drainage’ were considered for disaggregation of water management, because the number of available data were not adequate to evaluate other drivers. For example, other factors such as climate were not considered due to limited number of data.

## Annex 11A.4 Estimation of Default Emission Factor(s) for EF<sub>3PRP</sub>

We combined the dataset recently collated by Cai & Akiyama (2016) with 27 additional studies to derive EF<sub>3PRP</sub> factors (Yamulki *et al.* 1998; Galbally *et al.* 2005; Liebig *et al.* 2008; Cardenas *et al.* 2016; Di *et al.* 2016; Hoogendoorn *et al.* 2016; Hyde *et al.* 2016; Krol *et al.* 2016; Li *et al.* 2016; Luo *et al.* 2016; Marsden *et al.* 2016; Misselbrook *et al.* 2016; Nichols *et al.* 2016; O'Connor *et al.* 2016; Owens *et al.* 2016; Pelster *et al.* 2016; Ward *et al.* 2016; Balvert *et al.* 2017; Byrnes *et al.* 2017; Forrestal *et al.* 2017; Marsden *et al.* 2017; Owens *et al.* 2017; Thomas *et al.* 2017a, b; Tully *et al.* 2017; van der Weerden *et al.* 2017; Cardoso *et al.* 2018; Chadwick *et al.* 2018; Nichols *et al.* 2018). We excluded studies which:

- Were non-peer-reviewed publications;
- Were conducted in the laboratory and greenhouses, and modelling studies (only field studies were selected);
- Were conducted in flooded rice fields;
- Included fertiliser (manure or synthetic) additions;
- Were less than 30 days in duration; and
- Related to excreta treated with inhibitors.

The updated dataset contained 461 EF<sub>3PRP</sub> values, with urine dominating the data, representing 326 (= 71 percent) of the values. Data were collated from studies where excreta was deposited onto either pasture or forage crops such as brassicas or fodder beets. Nitrogen sources were dung, real urine and artificial urine. Artificial urine represented a substantial number of data values (72).

Research has shown that increasing soil water content generally results in greater N<sub>2</sub>O production and emission from urine patches (de Klein *et al.* 2003, van der Weerden *et al.* 2014). Therefore, EF<sub>3PRP</sub> data have been disaggregated by climate (dry and wet) for compilers with suitable activity data to allow disaggregation of livestock classes by climate. The division between wet and dry in the tropics is based on 1000 mm of precipitation (greater than 1000 mm equating with wet/moist climate), and the division in the temperate region is based on mean annual precipitation:potential evapotranspiration ratio of 1 (greater than 1 equating with a wet/moist climate). There are currently insufficient observations in the dataset to allow further climate disaggregation. Aggregated values are also provided for compilers that are not able to disaggregate PRP N inputs by climate.

Disaggregated excreta EF<sub>3PRP</sub> values for cattle in wet and dry climates and sheep in wet and dry climates were calculated from the urine and dung EF<sub>3PRP</sub> values reported in Table 4A.1, assuming a urine:dung nitrogen ratio of 0.66:0.34 (Kelliher *et al.* 2014). Disaggregated and aggregated excreta EF<sub>3PRP</sub> values are shown in Table 11.1. There was no difference in excreta EF<sub>3PRP</sub> for sheep when disaggregated into wet and dry climates, therefore only an aggregated value is provided.

The 95 percent confidence intervals were calculated using the 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of the data. Where urine and dung values have been aggregated to determine 'excreta' values, the 95 percent confidence intervals for urine and dung values have been converted to a proportion of the mean (see Fig. 3.3b in Volume 1, Chapter 3 'Uncertainties') and weighted according to the urine:dung nitrogen ratio. These weighted proportions were then used to estimate the 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile of the excreta values.

To determine whether there were significant differences in excreta EF<sub>3</sub> values between different categories (e.g. cattle vs. sheep), the data were analysed using a linear model. Excreta type (dung vs. urine vs. artificial urine), livestock type (cattle vs. sheep), land use (pastoral vs. forage crop) and climate (wet vs. dry) were added as fixed effects. There were very few data obtained from the same site, therefore site was not included in the model as a random effect. Due to its non-normal distribution, however, data was log transformed using a log (x + a) approach, (where a = 0.25 percent). An a term was added due to the presence of several negative values.

Results showed a significant difference between real urine and artificial urine EF<sub>3PRP</sub> values (P = 0.05). However, the analysis of data from two of the studies that included both real urine and artificial urine at similar N loads (de Klein *et al.* 2003; Chadwick *et al.* 2018) showed urine type (real vs artificial) had no significant effect on EF<sub>3PRP</sub> (P = 0.88, n = 16). On this basis, all artificial urine data were included, adding considerably more observations to the dataset (i.e., 63 additional observations).

Excreta type and animal type were highly significant (both P < 0.001), while there was a significant interaction between climate and animal type (P = 0.04). EF<sub>3PRP</sub> values for cattle and sheep dung and urine, in wet and dry climates are shown in Table 4A.1.

Compilers may improve their inventories with a Tier 2 method if activity data can be partitioned into dung and urine to produce a country-specific urine:dung ratio. This methodology will require data on N content of different forages and feeds and the amount of feed consumed by livestock (MPI, 2014).

**TABLE 4A.1**  
**EF VALUES FOR CATTLE AND SHEEP DUNG AND URINE, IN WET AND DRY CLIMATES**

Livestock type	Excreta type	Climate			
		Wet		Dry	
		mean	2.5 <sup>th</sup> to 97.5 <sup>th</sup> percentile, n <sup>A</sup>	mean	2.5 <sup>th</sup> to 97.5 <sup>th</sup> percentile, n <sup>A</sup>
Cattle	Urine	0.0077	0.0003 – 0.0382, 279	0.0032	0.0003 – 0.0093, 11
	Dung	0.0013	0.0000 – 0.0053, 107	0.0007	0.0001 – 0.0012, 6
Sheep	Urine	0.0039	0.0004 – 0.0180, 35	0.0031 <sup>B</sup>	0.0004 – 0.0091, 13 <sup>B</sup>
	Dung	0.0004	-0.0019 – 0.0027, 21	0.0021 <sup>C</sup>	-0.0001 – 0.0091, 7 <sup>C</sup>

<sup>A</sup> The 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile range reflect the 95% confidence interval for the mean.

<sup>B</sup> There were only two data for sheep urine in dry climates, with a mean value of 0.0027. Because this mean value was similar to the cattle urine in dry climates mean of 0.0032, data from both livestock types were pooled to allow a more robust mean and confidence interval for sheep urine under dry conditions.

<sup>C</sup> The dataset contained a single data value for sheep dung in dry climates (0.0105); this single value was greater than all the data for cattle dung in dry climates. To derive an approximation for a mean value and confidence interval for sheep dung in dry climates, this single sheep dung value was combined with cattle dung data from dry climates.

## Annex 11A.5 Estimation of Default Emission Factor(s) for EF<sub>4</sub>

In order to develop EF<sub>4</sub> values, review papers on indirect N<sub>2</sub>O emission from N deposition were collected from the published literature. We found two types of review papers, as described below.

### 1. Review papers on N addition experiments conducted in non-agricultural sites

In these experiments chemical N was applied to non-agricultural and non-wetland soil to simulate N deposition. Soil N<sub>2</sub>O emissions were measured in a zero-N control site and in a N treated site. One key advantage of this type of study is that N<sub>2</sub>O emissions from the zero-N control (N<sub>2</sub>O from N mineralisation, plant litter and N deposition) could be removed by subtracting the associated emissions from the treatment plots. The EF was computed as:

$$\text{EF (percent)} = (\text{N}_2\text{O}_{\text{N treatment}} - \text{N}_2\text{O}_{\text{control}}) / \text{N input} * 100$$

However, the disadvantage is that N application rates are often higher than actual N deposition rates. Regardless, the estimated EF values from these studies were the same order of magnitude to the EF<sub>1</sub> values estimated for this report (Table 5A.1), at least given that most of experiments relevant for estimating new EF<sub>4</sub> factors were conducted in temperate wet climate zones.

References	n	Mean EF (%)	SD	Note
Aronson & Allison (2012)	93	1.9	3.1	Data with measurement period of less than 90 days were excluded.
Liu & Greaver (2009)	42	0.87	0.25	—

### 2. Review papers on N<sub>2</sub>O emission and N deposition conducted in non-agricultural sites

In these experiments N<sub>2</sub>O emission and N deposition were measured concurrently in non-agricultural and non-wetland sites, and the EF was calculated as follows:

$$\text{EF (\%)} = \text{N}_2\text{O} / \text{N deposition} * 100$$

The advantage of this type of study is that actual N deposition rates were measured at these sites. However, the disadvantage is that EF does not exclude N<sub>2</sub>O from a zero-N control (N<sub>2</sub>O from N mineralisation), and therefore the influence of N deposition could not be isolated from other sources of N<sub>2</sub>O emissions. In general, the EF values of these studies were higher than those from N addition experiments in non-agricultural sites (Table 5A.2), probably because the resulting EFs did not exclude N<sub>2</sub>O from N mineralisation and plant litter as well as other sources of N inputs. This could cause double counting because the other sources of N are already addressed in other calculations for direct and indirect N<sub>2</sub>O emissions.

References	n	Mean EF (%)	SD	Note
Bühlmann <i>et al.</i> (2015)	57	7.0	8.7	Mean was calculated from Table S1
van der Gon & Bleeker (2005)	21	3.8	4.1	Weighted mean was calculated from Table 3
de Vries <i>et al.</i> (2011)	67	7.3	7.5	Estimated data were excluded

Therefore, considering that N addition experiments conducted in non-agricultural sites reported similar EF values as EF<sub>1</sub> results from our analysis, we decided to use the same emission factors as EF<sub>1</sub> for EF<sub>4</sub>. Disaggregation is only considered for climate type due to the absence of dependence of EF<sub>4</sub> upon the form (organic or synthetic) of original N input that volatilised. The EF<sub>4</sub> was disaggregated by wet and dry climates, as indicated in Table 2A.2 of Annex 11A.2.

## Annex 11A.6 Estimation of Default Emission Factor(s) for EF<sub>5</sub>

We collected peer-reviewed papers on EF<sub>5</sub> for in situ field studies (Tian *et al.* 2019). The final dataset contained 254 data observations (EF<sub>5g</sub>: n = 101, EF<sub>5r</sub>: n = 91, EF<sub>5e</sub>: n = 23).

The EF<sub>5g</sub>, EF<sub>5r</sub> and EF<sub>5e</sub> are defined as:

EF<sub>5g</sub>: groundwater (soil solution and lysimeter leaching water were not included), spring, surface drainage, and upstream emissions (upstream supersaturated with N<sub>2</sub>O, N<sub>2</sub>O emitted mainly from degassing of groundwater).

EF<sub>5r</sub>: rivers, reservoirs (including lake and pond), and downstream emissions (supersaturated N<sub>2</sub>O was already degassed and N<sub>2</sub>O mainly produced by nitrification/denitrification in situ).

EF<sub>5e</sub>: estuary emissions (only including inner estuaries or lower reaches of river that are close to the river mouth, while outer estuaries and coastal seawater are excluded).

We found a lack of consistency in dividing EF<sub>5g</sub> and EF<sub>5r</sub> for streams based on the literature, at least in some studies. Here, we categorized data into EF<sub>5g</sub> based on upstream supersaturated with N<sub>2</sub>O where N<sub>2</sub>O is emitted mainly from degassing of groundwater, and EF<sub>5r</sub> based on downstream, supersaturated N<sub>2</sub>O that was already degassed and N<sub>2</sub>O mainly produced by nitrification/denitrification in situ.

Note that the N sources in most rivers include both agricultural (mainly arable farming and grazing grassland) and urban sewage. However, we found it was difficult to separate the different N sources based on the limited information in the publications. Therefore, our dataset on EF<sub>5r</sub> includes non-agricultural N source.

Most estuaries are impacted by urban waste water and aquaculture in addition to agriculture. However, all available data were included because of their limited number.

Arithmetic mean emission factors were calculated as follows; EF<sub>5g</sub>: 0.0060 kg N<sub>2</sub>O–N/kg NO<sub>3</sub>-N in the water, EF<sub>5r</sub>: 0.0026 kg N<sub>2</sub>O–N/kg NO<sub>3</sub>-N in the water and EF<sub>5e</sub>: 0.0026 kg N<sub>2</sub>O–N/kg NO<sub>3</sub>-N in the water.

EF<sub>5</sub> was calculated as follows:

$$EF_5 = EF_{5g} + EF_{5r} + EF_{5e}$$

Uncertainty range is based on the 2.5<sup>th</sup> to 97.5<sup>th</sup> percentile.

## Annex 11A.7 Estimation of Default Factor(s) for Frac<sub>GASF</sub>

The Tier 1 aggregated default NH<sub>3</sub> + NO<sub>x</sub> EF for emissions from synthetic fertiliser has been derived as the arithmetic mean of default EF values for the different types of individual N fertilisers. Individual fertiliser types were weighted according to their use in the period 2007-2015 as reported by the International Fertilizer Industry Association (IFA) (Table 7A.1), based on world fertiliser usage. For countries that require inventories for air pollutant emissions, there is a continuous update of NH<sub>3</sub> and NO EF values through the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2016).

Fertiliser product	2007-2015	%
Ammonia (direct application)	35823	4
AS	27931	3
Urea	442550	50
AN	53676	6
CAN	29624	3
Nitrogen solutions	46870	5
Other N straight	45722	5
AP	55692	6
Other NP (N)	17911	2
N K compound (N)	2372	0.3
N P K compound (N)	127227	14

Where Ammonia (direct application) = anhydrous ammonia, AS= ammonium sulphate, AN=Ammonium nitrate, CAN= calcium ammonium nitrate and AP= ammonium phosphate

For disaggregation, we divided all fertiliser usage into 4 types of fertiliser categories based on their basic chemical composition: urea, ammonium-based (ammonia-direct application, AS, and AP), nitrate-based (N K compound-N) and ammonium-nitrate-based (AN, CAN, Nitrogen solutions, Other N straight, Other NP-N and N P K compound-N). For weighting purposes, assumptions on chemical compositions had to be considered for different fertiliser types reported by IFA for compound fertilisers and for those fertilisers that had not been tested in our experimental datasets. We assumed that emissions from these fertiliser types were those obtained from the mean value of a mix of different straight fertilisers for different IFA fertiliser products, in the absence of clear statistics on their composition and based on qualitative assessments (Table 7A.2).

Fertiliser product	Fertiliser Mix
Nitrogen solutions	Urea (50%), AN (25%), CAN (25%)
Other N straight	AN (50%), CAN (50%)
Other NP (N)	AN (50%), CAN (50%)
AP	MAP (50%), DAP (50%)
N K compound (N)	Sodium Nitrate
N P K compound (N)	AN (50%), CAN (50%)

Where AN = Ammonium nitrate, CAN = calcium ammonium nitrate AS = ammonium sulphate, AP = ammonium phosphate, MAP = monoammonium phosphate and DAP = diammonium phosphate.

For NH<sub>3</sub>, we used the datasets of peer-reviewed studies from the Bouwman *et al.* (2002) meta-analysis and the recently published dataset collated by Pan *et al.* (2016). A total number of 273 studies were used, and included most of the common fertiliser types. Although data were primarily obtained from studies comparing NH<sub>3</sub> emissions

from different fertiliser types, we also included emissions data from other studies that were conducted for other purposes (e.g., assessing effect of urease inhibitors, application rate, and amendments) by using the EF values from the control treatments.

For NO<sub>x</sub>, we used the dataset of peer-reviewed studies collated by Liu *et al.* (2017). For the Tier 1 EF, we used the data from 54 studies (171 field measurements) comprising information on NO emissions by aggregating data from all types of fertiliser. Furthermore, to develop the disaggregated NO<sub>x</sub> EFs, we estimated values that were specific to different fertiliser types.

Median EF values for each fertiliser type for both NH<sub>3</sub> and NO<sub>x</sub> are shown in Table 7A.3. Median instead of mean values were used due to skewed right distribution of the data.

Fertiliser	Percentage lost as N (%)			number of studies		
	Total	NH <sub>3</sub> -N	NO <sub>x</sub> -N	Total	NH <sub>3</sub> -N	NO <sub>x</sub> -N
Urea	15.3	14.2	1.1	209	187	22
AS	10.2	9.5	0.7	41	37	4
AN	6.0	3.0	2.9	34	23	11
CAN	3.2	1.6	1.6	7	6	1
DAP	9.8	9.1	0.7	11	8	3
MAP	6.0	5.3	0.7	3	2	1
Sodium Nitrate	1.2	0.2	1.0	4	1	3
AA	3	2.9	0.1	2	1	1

Where AS = ammonium sulphate, AN = Ammonium nitrate, CAN = calcium ammonium nitrate, DAP = diammonium phosphate, MAP = monoammonium phosphate and AA = anhydrous ammonia.

EF values for NH<sub>3</sub> emissions were compared with those obtained using the method to predict NH<sub>3</sub> emissions in the current EMEP/EEA guidelines (EMEP/EEA, 2016). The EF for NH<sub>3</sub>-N from urea (14.2 percent) is lower than the range of 15.5-21 percent from current EMEP/EEA guidelines values, which depend on soil pH and temperature conditions, but similar to Bouwman *et al.* (2002) and Pan *et al.* (2016) values. Discrepancies are likely to arise based on the assumptions taken and analytical choices (e.g. use of mean *vs.* median). Moreover, it must be noted that future revisions to the EMEP/EEA guidebook are expected to use most of the same data utilized in this report and therefore, EFs may be updated in the EMEP/EEA guidebook (2016).

## Annex 11A.8 Estimation of Default Factor for Frac<sub>GASM</sub>

Review papers on NH<sub>3</sub> and NO were collected to derive the fraction of N that is volatilised. Field measurement data with manure or slurry application and excreta patches were extracted from the published literature (see below). Field measurement data with chemical N application as well as studies with a focus on mitigation technologies, such as nitrification inhibitors or urease inhibitors were excluded from this analysis.

For NH<sub>3</sub>, the arithmetic mean was calculated from Bouwman *et al.* (2002) and Cai & Akiyama (2016). For NO, the mean and uncertainty range were calculated from Cai & Akiyama (2016) and Liu *et al.* (2017). The difference between mean EF for cattle and sheep excreta was negligible, thus livestock type was not considered. The default Frac<sub>GASM</sub> was derived as the sum of the arithmetic mean of NH<sub>3</sub> EF and NO<sub>x</sub> EF. The uncertainty range was based on 2.5<sup>th</sup> and 97.5<sup>th</sup> percentile.

TABLE 8A.1 EMISSION FACTORS FOR NH <sub>3</sub> -N AND NO <sub>x</sub> -N (N APPLIED OR DEPOSITED) <sup>-1</sup> FROM MANURE APPLICATION AND EXCRETA PATCHES				
	n	Mean	Range (2.5 <sup>th</sup> to 97.5 <sup>th</sup> percentile)	Source of data
NO <sub>x</sub>	40	0.015	0 – 0.149	Liu <i>et al.</i> (2017)
NH <sub>3</sub>	172	0.197	0 – 0.295	Bouwman <i>et al.</i> (2002), Cai & Akiyama (2016)
NO <sub>x</sub> + NH <sub>3</sub>	212	0.212	0 – 0.312	References listed above

## **Annex 11A.9 Estimation of Default Factor for Frac<sub>LEACH</sub>(H)**

We collected review papers (Di & Cameron 2002; Cai & Akiyama 2016) and original papers on N leaching/runoff for this analysis (Moreno *et al.* 1996; Diez *et al.* 1997; Catt *et al.* 1998; Sogbedji *et al.* 2000; Asadi *et al.* 2002; Readman *et al.* 2002; Ren *et al.* 2003; Dauden & Quilez 2004; Dauden *et al.* 2004; Diez *et al.* 2004; Bakhsh *et al.* 2005; Basso & Ritchie 2005; Gehl *et al.* 2005; Fang *et al.* 2006; Li *et al.* 2006; Diez-Lopez *et al.* 2008; Conrad & Fohrer 2009; Zhu *et al.* 2009; Aronsson & Stenberg 2010; Bakhsh *et al.* 2010; Salmeron *et al.* 2010; Yague & Quilez 2010; Claret *et al.* 2011; Huang *et al.* 2011; Gallejones *et al.* 2012; Perego *et al.* 2012; Sorensen & Ruback 2012; Tafteh & Sepaskhah 2012; Wang *et al.* 2012). Only peer-reviewed studies that used lysimeters and in-situ field measurements were included. Studies conducted in the laboratory were excluded, along with studies that used mitigation technologies such as nitrification inhibitor. The final dataset contained 355 data observations from which the arithmetic mean and uncertainty range for a 95 percent confidence interval were calculated.

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