CHAPTER 11

N_2O EMISSIONS FROM MANAGED SOILS, AND CO_2 EMISSIONS FROM LIME AND UREA APPLICATION

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11.1 INTRODUCTION

No refinement

11.2 N_2O EMISSIONS FROM MANAGED SOILS

This section has further elaboration of the methods and updates.

This section presents the methods and equations for estimating total national anthropogenic emissions of N_2O (direct and indirect) from managed soils. The generic equations presented here can also be used for estimating N_2O within specific land-use categories (e.g., urban landscapes) 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_2). 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_2O 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_2O 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 NH_3 and NO_x from managed soils and from fossil fuel combustion and biomass burning, and the subsequent redeposition of these gases and their products NH_4^+ and NO_3^- to soils and waters; and (ii) after leaching and runoff of N, mainly as NO_3^-, from managed soils. The principal pathways are illustrated in Figure 11.1.

Direct emissions of N_2O 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 residues 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_2O emissions

In most soils, an increase in available N enhances nitrification and denitrification rates which then increase the production of N_2O. 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_2O emissions from managed soils:

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

- N in crop residues (above-ground and below-ground), including from N-fixing crops [1] and from forages during pasture renewal [2] (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) [3] (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_2O emissions from managed soils are estimated using Equation 11.1 as follows:

EQUATION 11.1

DIRECT N_2O EMISSIONS FROM MANAGED SOILS (TIER 1)

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

Where:

$$N_2O-N_{N\ inputs} = \left[\begin{array}{l}\left[\left(F_{SN}+F_{ON}+F_{CR}+F_{SOM}\right)\bullet EF_1\right]+\\ \left[\left(F_{SN}+F_{ON}+F_{CR}+F_{SOM}\right)_{FR}\bullet EF_{1FR}\right]\end{array}\right]$$

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

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

Where:

N_2O_{Direct} –N = annual direct N_2O–N emissions produced from managed soils, kg N_2O–N yr^{-1}

N_2O–$N_{N\ inputs}$ = annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N yr^{-1}

N_2O–N_{OS} = annual direct N_2O–N emissions from managed organic soils, kg N_2O–N yr^{-1}

N_2O–N_{PRP} = annual direct N_2O–N emissions from urine and dung inputs to grazed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}

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[1] Biological nitrogen fixation has been removed as a direct source of N_2O 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_2O 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 *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).

[2] 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.

[3] 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).

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_2O emissions from the N in sewage sludge), kg N yr^{-1}

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^{-1}

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^{-1}

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^{-1} (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)

EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$(Table 11.1)

EF_{1FR} is the emission factor for N_2O emissions from N inputs to flooded rice, kg N_2O–N (kg N input)$^{-1}$ (Table 11.1) [4]

EF_2 = emission factor for N_2O emissions from drained/managed organic soils, kg N_2O–N ha^{-1} yr^{-1}; (See guidance in 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, 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_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, kg N_2O–N (kg N input)$^{-1}$; (Table 11.1) (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)

Conversion of N_2O–N emissions to N_2O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O\text{–}N \bullet 44/28$$

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 [5]:

EQUATION 11.2
DIRECT N_2O EMISSIONS FROM MANAGED SOILS (TIER 2)

$$N_2O_{Direct}-N = \sum_i \left(F_{SN} + F_{ON}\right)_i \bullet EF_{1i} + \left(F_{CR} + F_{SOM}\right) \bullet EF_1 \;+\; N_2O\text{–}N_{OS} \;+\; N_2O\text{–}N_{PRP}$$

Where:

EF_{1i} = emission factors developed for N_2O emissions from synthetic fertiliser and organic N application under conditions *i* (kg N_2O–N (kg N input)$^{-1}$); *i* = 1, …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}). Countries can develop emission factors specific to mitigation options such as the application of nitrification inhibitors (Akiyama et al., 2010; Ruser and Schulz, 2015; Gilsanz et al., 2016). Countries can also consider an exponential response of N_2O emissions to

[4] 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.

[5] 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.

Figure 11.1 Schematic diagram illustrating the sources and pathways of N that result in direct and indirect N_2O 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_3 and NO_x from agricultural and non-agricultural sources, deposition of these gases and their products NH_4^+ and NO_3^-, and consequent indirect emissions of N_2O 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.

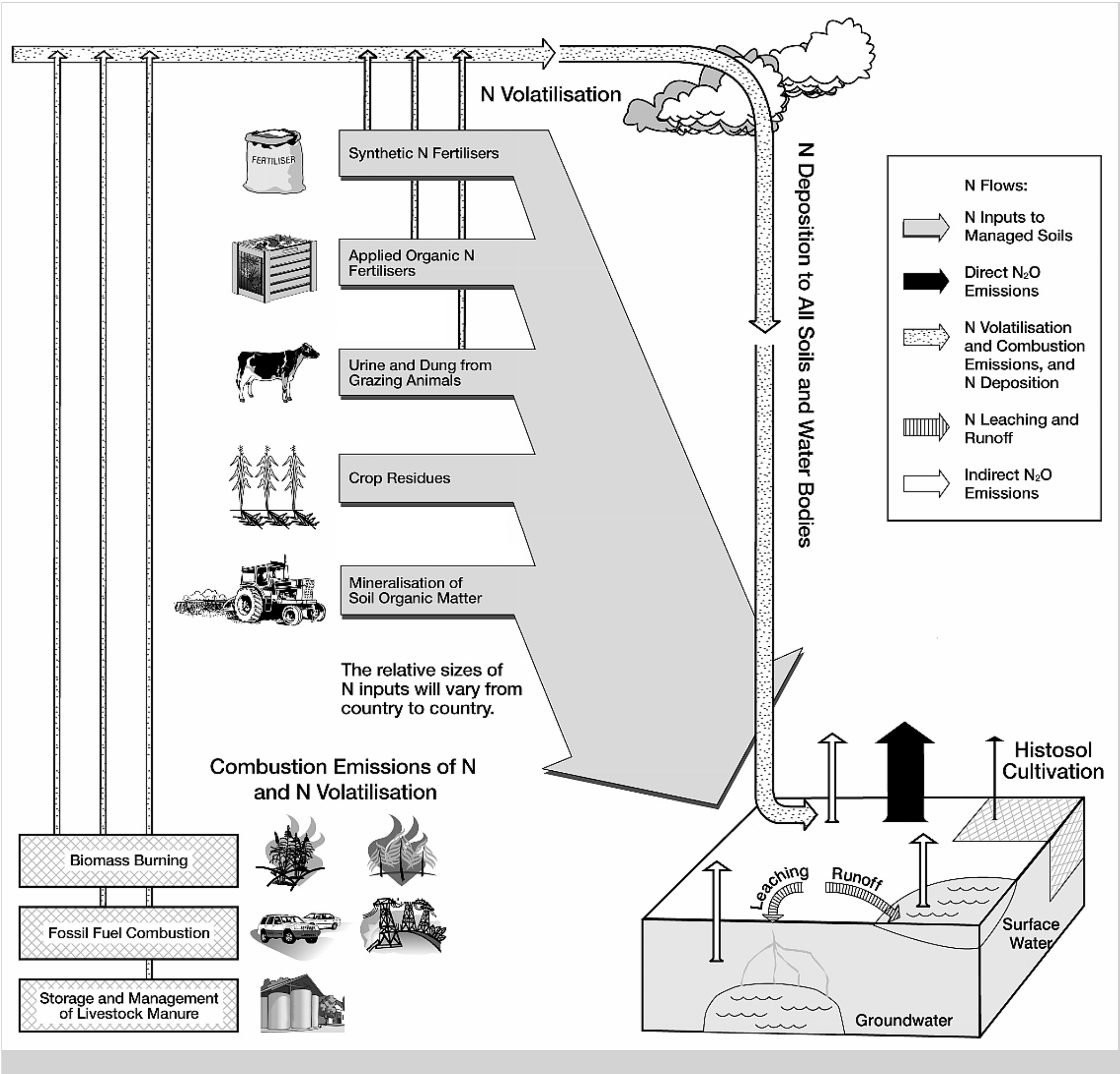
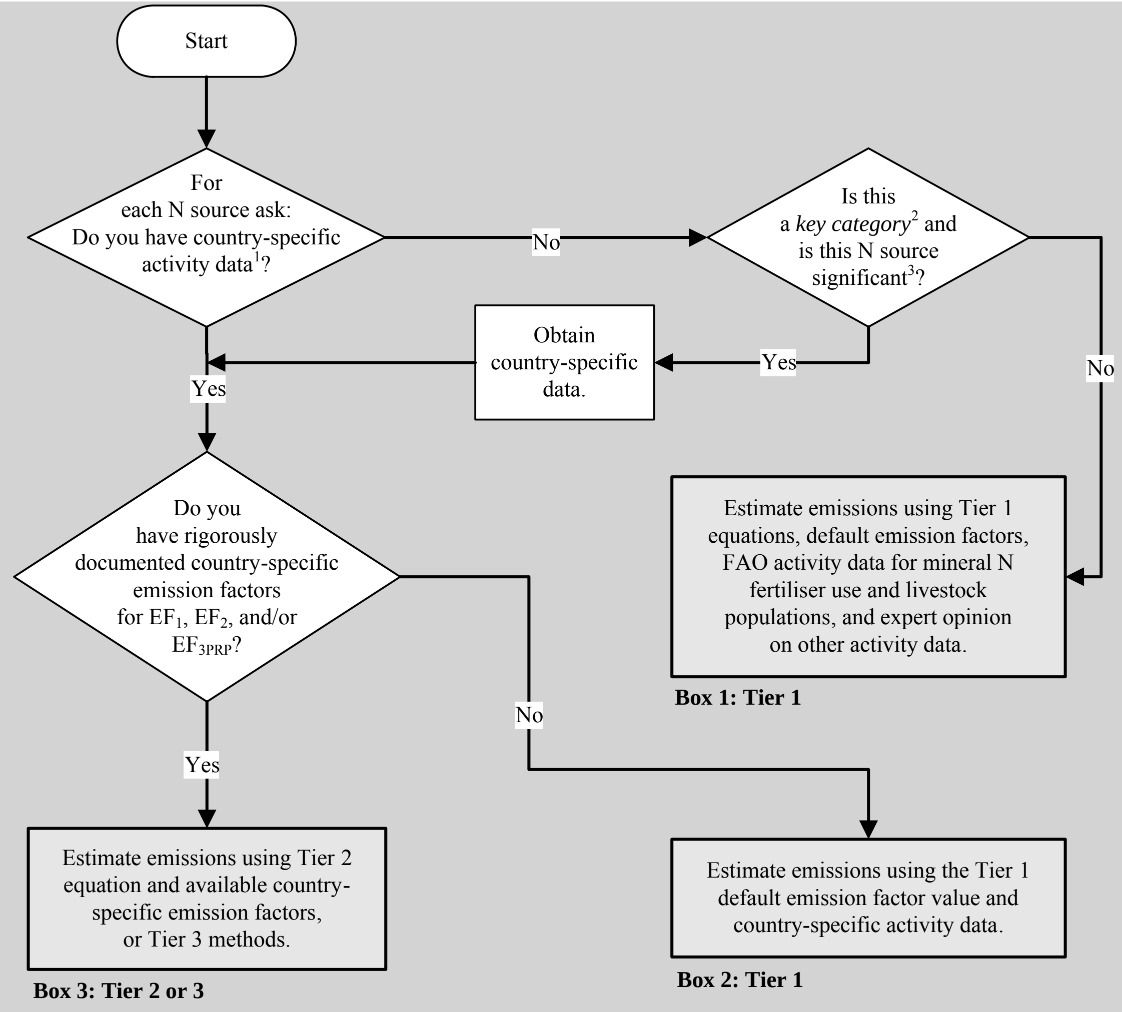


Figure 11.2 Decision tree for direct N_2O emissions from managed soils



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.

N application if developing country-specific emission factors (van Groenigen et al., 2010; Shcherbak et al., 2014). This method will require activity data on specific fertiliser application rates to soils in order to apply the rate-specific emission factors that capture the exponential response[6]. 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 $N_2O–N$ emissions to N_2O emissions for reporting purposes is performed by using the following equation:

$$N_2O = N_2O–N \bullet 44/28$$

According to Equations 11.1, direct emissions of N_2O from managed soils are calculated in the Tier 1 approach on the basis of total N from animal manure applied to soils. The processes of run-off of N, volatilization of NH_3

[6] The Tier 1 method is designed as a simple method for estimating direct N_2O 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 soils, which is needed for emission factors that are adjusted with application rates. However, variable emission factors can be developed with the Tier 2 method.

and NOx, emissions of N_2O, and leaching of N, however, do not occur simultaneously but in a sequence, with the peak of run-off and NH_3+NOx volatilization happening before emissions of N_2O and losses of N through leaching. For example, an application technique affecting the volatilization rate of NH_3+NO_x is likely to change the flow rates of subsequent processes. To illustrate, injecting slurry instead of broadcasting increases the availability of N for N_2O emissions and N-leaching. It is therefore good practice to carefully assess such 'pollution swapping' effects when implementing higher Tier approaches and adopt the N-flow principle when estimating direct N_2O emissions. The same applies when estimating indirect N_2O emissions from leaching and runoff (see Section 11.2.2.1). This adoption can be achieved by accounting for the increased pool of nitrogen which is available for direct N_2O emissions (and nitrogen leaching).

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_2O 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_2O emissions [7] .Guidance that provides a sound scientific basis for the development of a Tier 3 Model-based Accounting System is given in Chapter 2, Section 2.5.

11.2.1.2 CHOICE OF EMISSION FACTORS

Tiers 1 and 2

Three emission factors (EF) are needed to estimate direct N_2O 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_1) refers to the amount of N_2O 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_2) refers to the amount of N_2O emitted from an area of drained/managed organic soils, and the third EF (EF_{3PRP}) estimates the amount of N_2O 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_2, 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_1 has been set at 1% of the N applied to soils or released through activities that result in mineralisation of organic matter in mineral soils [8]. Given the growing number of studies highlighting the role of climate and fertiliser form in determining EF_1 (Flechard 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 climate the default value has been set at 0.7% of organic N inputs and 1.7% of synthetic N inputs. In dry climate the default value has been set at 0.5% of N inputs – organic and synthetic forms confounded. These alternative EF_1 can be used by countries that are able to disaggregate their activity data accordingly. There are data to suggest that the emission factor could also be further disaggregated as part of the 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; irrigation and type of crop with differences between legumes, non-leguminous arable crops, and grass) (e.g. Cayuela *et al.*, 2017; Rochette *et al.*, 2018; Wagner-Riddle et al., 2017). Countries 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 values for EF_2 are provided in the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Chapter 2, Table 2.5. The default value for EF_{3PRP} is 0.4% of the N deposited by all animal types except 'sheep' and 'other' animals. For these latter species, a default emission factor of 0.3% of the N deposited may be used [9]. When disaggregated by climate and animal type, for wet climate EF_{3PRP} is 0.6% for all

[7] Natural N_2O 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.

[8] The value of EF_1 draw on a much larger number of measurements (see Annex 11A.2) than were available for the previous value used for EF_1 in the 2006 IPCC Guidelines (Bouwman *et al.*, 2002a,b; Stehfest and Bouwman, 2006; Novoa and Tejeda, 2006).

[9] This is an update on the 2006 IPCC Guidelines, with over 400 cattle and sheep dung and urine EF_3 values collated from 13 countries (See Annex 11.3). As noted in the 2006 IPCC Guidelines, reasons for the lower EF_{3PRP} for sheep include more even urine distribution (smaller and more frequent urinations), and smaller effects on soil compaction during grazing. There

animal types except ‘sheep’ and ‘other’ animals and 0.3% for sheep and other animals. For dry climate, EF_{3PRP} is 0.3% for all animal types except ‘sheep’ and ‘other’ animals and 0.2% for sheep and other animals.

UPDATED TABLE 11.1
DEFAULT EMISSION FACTORS TO ESTIMATE DIRECT N_2O EMISSIONS FROM MANAGED SOILS

Emission factor	Aggregated		Disaggregated		
	Default value	Uncertainty range	Disaggregation	Default value	Uncertainty range
EF_1 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[1] [kg N_2O–N (kg N)$^{-1}$]	0.010	0.000 – 0.020	Synthetic fertilizer inputs[2] in wet climates	0.017	0.013 – 0.020
			Other N inputs[3] in wet climates	0.007	0.001 – 0.013
			All N inputs in dry climates	0.005	0.000 – 0.012
EF_{1FR} for flooded rice fields[4] [kg N_2O–N (kg N)$^{-1}$]	0.004	0.000 – 0.029	Continuous flooding	0.003	0.000 – 0.010
			Single and multiple drainage	0.005	0.000 – 0.016
$EF_{3PRP, CPP}$ for cattle (dairy, non-dairy and buffalo), poultry and pigs[1] [kg N_2O–N (kg N)$^{-1}$]	0.004	0.001 – 0.025	Wet climates	0.006	0.001 – 0.026
			Dry climates	0.003	0.001 – 0.007
$EF_{3PRP, SO}$ for sheep and ‘other animals’[1] [kg N_2O–N (kg N)$^{-1}$]	0.003	0.001 – 0.012	Wet climates	0.003	0.001 – 0.012
			Dry climates	0.002	0.001 – 0.003

Notes:

EF_1: From the databases by Albanito et al. (2017), Cayuela et al. (2017), Liu et al. (2017), Stehfest and Bouwman (2006), Rochette et al. (2018), and van Lent et al. (2015). Uncertainty range of disaggregated EF_1 based on the 95% confidence interval of fitted values. Uncertainty range of aggregated EF_1 based on the lowest and highest uncertainties of disaggregated EF_1 (See methods, data and results in Annex 11A.2).

EF_{1FR}: From the databases by Akiyama et al. (2005), Albanito et al. (2017), Cayuela et al. (2017). Uncertainty range based on the 2.5th to 97.5th percentile (See methods and data in Annex 11A.3).

$EF_{3PRP, CPP}$ and $EF_{3PRP, SO}$: Source of data: Balvert et al. 2017; Byrnes et al. 2017; Cai and Akiyama, 2016; Cardenas et al. 2016; Cardoso et al. 2018; Chadwick et al. 2018; Di et al. 2016; Forrestal et al. 2017; Hoogendoorn et al. 2016; Hyde et al. 2016; Krol et al. 2016; Li et al. 2016; Liebig et al. 2008; Luo et al. 2016; Marsden et al. 2016, 2017; Misselbrook et al. 2016; Nichols et al. 2016, 2018; O’Connor et al. 2016; Owens et al. 2016, 2017; Pelster et al. 2016; Thomas et al. 2017a,b; Tully et al. 2017; van der Weerden et al. 2017; Ward et al. 2016; Yamulki et al. 1998. Uncertainty range based on the 2.5th to 97.5th percentile (See methods and data in Annex 11A.4).

[1]Disaggregation of EF_1 and EF_{3PRP} by climate: Wet climate relates to temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climate relates to temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (cf. Chapter 3 of Vol. 4.). In wet climate, the EF_1 is further disaggregated by synthetic fertilizer N inputs and other N inputs.

[2] This emission factor should be used for synthetic fertilizer applications, and fertilizer mixtures that include both synthetic and organic forms of N.

[3] Other N input refers to organic amendments/fertilisers, N in crop residues, and mineralized N from soil organic matter decomposition.

[4] Disaggregation of EF_{1FR}: Single and multiple drainage also include alternate wetting and drying. Disaggregated EF_{1FR} for rain-fed and deep-water systems not provided due to lack of data. The EF_1 should be used for upland rice.

are no or very limited data for N_2O 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 nitrogen excretion rates and patterns that are more similar to sheep than to cattle. For disaggregation of EF_3 by dung and urine nitrogen for each livestock group, see Annex 11.3.

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_{SN}, F_{ON}, F_{PRP}, F_{CR}, F_{SOM}, F_{OS}) that are needed for the Tier 1 and Tier 2 methodologies (Equations 11.1 and 11.2).

Applied synthetic fertiliser (F_{SN})

The term F_{SN} refers to the annual amount of synthetic N fertiliser applied to soils [10]. 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 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://faostat.fao.org/) on synthetic fertiliser consumption, can be used. 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_{ON})

The term "applied organic N fertiliser" (F_{ON}) 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_{ON}) 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^{-1}

F_{AM} = annual amount of animal manure N applied to soils, kg N yr^{-1}

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^{-1}

F_{COMP} = annual amount of total compost N applied to soils (ensure that manure N in compost is not double-counted), kg N yr^{-1}

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

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 $Frac_{FUEL}$, $Frac_{FEED}$, $Frac_{CNST}$.

[10] For the Tier 1 approach, the amounts of applied mineral nitrogen fertilisers (F_{SN}) and of applied organic nitrogen fertilisers (F_{ON}) are no longer adjusted for the amounts of NH_3 and NO_x volatilisation after application to soil. This is a change from the methodology described in the *1996 IPCC Guidelines*. The reason for this change is that field studies that have determined N_2O 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_2O–N emitted / total amount of N applied, and not from: fertiliser-induced N_2O–N emitted / (total amount of N applied – NH_3 and NO_x 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_2O emissions. Countries using Tier 2 or Tier 3 approaches should be aware that correction for NH_3/NO_x volatilisation after mineral or organic N application to soil may be required depending on the emission factor and/or the inventory methodology used.

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

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

Where:

F_{AM} = annual amount of animal manure N applied to soils, kg N yr^{-1}

$N_{MMS\ Avb}$ = amount of managed manure N available for soil application, feed, fuel or construction, kg N yr^{-1} (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)

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

Where:

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

$N_{(T)}$ = 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^{-1} yr^{-1} (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[11] (see Chapter 10, Section 10.5)

Crop residue N, including N-fixing crops and forage/ pasture renewal, returned to soils, (F_{CR})

The term F_{CR} refers to the amount of N in crop residues (above-ground and below-ground), including N-fixing crops, returned to soils annually [12]. It also includes the N from N-fixing and non-N-fixing forages mineralised during forage or pasture renewal [13]. 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_2O 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

[11] In the livestock section, pasture, range and paddock is referred to as one of the manure management systems denoted as "S".

[12] The equation to estimate F_{CR} has been modified from the previous *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_{CR}. As a result, F_{CR} 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.

[13] The inclusion of nitrogen from forage or pasture renewal is a change from previous *1996 IPCC Guidelines*.

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.

UPDATED EQUATION 11.6

N FROM CROP RESIDUES AND FORAGE/PASTURE RENEWAL (TIER 1)

$$F_{CR} = \sum_{T}\left[AGR_{(T)} \bullet N_{AG(T)} \bullet \left(1 - Frac_{Remove(T)} - (Frac_{Burnt(T)} \bullet C_f\right)\right] + \left[BGR_{(T)} \bullet N_{BG(T)} \right]$$

$$AGR_{(T)} = Crop_{(T)} \bullet R_{AG(T)} \bullet Area_{(T)} \bullet Frac_{Renew(T)}$$

$$BGR_T = Crop_T \bullet \left(1 + R_{AG(T)}\right) \bullet R:S_{(T)} \bullet Area_{(T)} \bullet Frac_{Renew(T)}$$

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^{-1}

$AGR_{(T)}$ = annual total amount of above-ground crop residue for crop *T*, kg d.m. ha^{-1}. (Use factors in Table 11.1A, or alternatively, the amount can be calculated using the method and data in Table 11.2)

$N_{AG(T)}$ = N content of above-ground residues for crop *T*, kg N (kg d.m.)$^{-1}$ (Table 11.1A)

$Frac_{Remove(T)}$ = 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 $Frac_{Remove}$ are not available, assume no removal

$Frac_{Burnt(T)}$ = 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. ha^{-1}

$N_{BG(T)}$ = N content of below-ground residues for crop *T*, kg N (kg d.m.)$^{-1}$, (Table 11.1A)

$Crop_{(T)}$ = harvested annual dry matter yield for crop *T*, kg d.m. ha^{-1}

$R_{AG(T)}$ = ratio of above-ground residues dry matter ($AG_{DM(T)}$) to harvested yield for crop *T* ($Crop_{(T)}$), kg d.m. (kg d.m.)$^{-1}$, (Table 11.1A)

$Area_{(T)}$ = total annual area harvested of crop *T*, ha yr^{-1}

$Frac_{Renew\ (T)}$ = fraction of total area under crop *T* that is renewed annually [14], dimensionless. For countries where pastures are renewed on average every X years, $Frac_{Renew}$ = 1/X. For annual crops $Frac_{Renew}$ = 1

$R:S_{(T)}$ = ratio of below-ground root biomass to above-ground biomass for crop *T*, kg d.m. (kg d.m.)$^{-1}$, (Table 11.1A)

T = crop or forage type

[14] This term is included in the equation to account for N release and the subsequent increases in N_2O emissions (e.g., van der Weerden *et al.*, 1999; Davies *et al.*, 2001), from renewal/cultivation of grazed grass or grass/clover pasture and other forage crops.

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://faostat.fao.org/).

Since yield statistics for many crops are reported as field-dry or fresh weight, a correction factor can 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 used in 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^{-1}

$Yield\_Fresh_{(T)}$ = harvested fresh yield for crop *T*, kg fresh weight ha^{-1}

DRY = dry matter fraction of harvested crop *T*, kg d.m. $(kg\ fresh\ weight)^{-1}$

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.

NEW TABLE 11.1A
DEFAULT VALUES FOR NAG(T) , NBG(T) , RAG(T), R:S(T) AND DRY TO BE USED IN EQUATIONS 11.6 AND 11.7

Crops	N content of above-ground residues ($N_{AG(T)}$)[a]	N content of below-ground residues ($N_{BG(T)}$)[a]	$R_{AG(T)}$ [b]	Ratio of below-ground biomass to above-ground biomass ($R:S_{(T)}$)[a]	Dry matter fraction of harvested product (DRY)[a]
Crops					
Generic value for crops not indicated below[c]	0.008	0.009	1.0	0.22	0.85
Generic Grains	0.006	0.009	1.3	0.22 (±16%)	0.88
Winter Wheat	0.006	0.009	1.3	0.23 (±41%)	0.89
Spring Wheat	0.006	0.009	1.3	0.28 (±26%)	0.89
Barley	0.007	0.014	1.2	0.22 (± 33%)	0.89
Oats	0.007	0.008	1.3	0.25 (± 120%)	0.89
Maize	0.006	0.007	1.0	0.22 (± 26%)	0.87
Rye	0.005	0.011	1.6	-	0.88
Rice	0.007	-	1.4	0.16 (± 35%)	0.89
Millet	0.007	-	1.4	-	0.90
Sorghum	0.007	0.006	1.4	-	0.89
Beans and Pulses	0.008	0.008	2.1	0.19 (± 45%)	0.91
Soybeans	0.008	0.008	2.1	0.19 (± 45%)	0.91
Potatoes and Tubers	0.019	0.014	0.4	0.20 (± 50%)[d]	0.22
Peanuts	0.016	-	1.0	-	0.94
Grasses and Forages					
Alfalfa	0.027	0.019	-	0.40 (± 50%)[e]	0.90
Non-legume hay	0.015	0.012	-	0.54 (± 50%)[e]	0.90
N-fixing forages	0.027	0.022	0.3	0.40 (± 50%)	0.90
Non-N-fixing forages	0.015	0.012	0.3	0.54 (± 50%)	0.90
Perennial Grasses	0.015	0.012	0.3	0.80 (± 50%)[f]	0.90
Grass-Clover Mixtures	0.025	0.016	0.3	0.80 (± 50%)[f]	0.90

a Source: 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.
b Source: 2000 IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Chapter 4 for RAG(T) except forages, grasses and grass-clover mixes, which are from the 2006 IPCC Guidelines, Chapter 11, and the generic value for all crops, which is the expert opinion of authors.
c It is assumed here that grass dominates the system by 2 to 1 over legumes.
d 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 are derived from Vangessel and Renner, 1990 (see Annex 11A.1) (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.
e This is based an estimate of root turnover in perennial systems. Default s.d.
f 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.

UPDATED TABLE 11.2
ALTERNATIVE METHOD AND DATA FOR ESTIMATING ABOVE-GROUND RESIDUE ($AGR_{(T)}$) [A]

Crop	Above-ground residue dry matter $AGR_{(T)}$ (kg d.m. ha^{-1}): $AGR_{(T)} = Crop_{(T)} * Slope_{(T)} + (Intercept_{(T)} * 1000)$				
	Slope	**± 2 s.d. as % of mean**	**Intercept**	**± 2 s.d. as % of mean**	**R^2 adj.**
Major crop types					
Grains	1.09	± 2%	0.88	± 6%	0.65
Beans & pulses[b]	1.13	± 19%	0.85	± 56%	0.28
Tubers[c]	0.10	± 69%	1.06	± 70%	0.18
Root crops, other[d]	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	-	-
Individual crops					
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[e]	1.09	± 50% default	0.88	± 50% default	-
Soybean[f]	0.93	± 31%	1.35	± 49%	0.16
Dry bean[g]	0.36	± 100%	0.68	± 47%	0.15
Potato[h]	0.10	± 69%	1.06	± 70%	0.18
Peanut (w/pod)[i]	1.07	± 19%	1.54	± 41%	0.63
Alfalfa	0.29[j]	± 31%	0	-	-
Non-legume hay	0.18	± 50% default	0	-	-

[a] Source: 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.

[b] 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.

[c] Average of other crops.

[d] Modelled after peanuts.

[e] No data for rye. Slope and intercept values are those for all grain. Default s.d.

[f] The average above-ground residue:grain ratio from all data used was 1.9.

[g] Ortega, 1988 (see Annex 11A.1). The average above-ground residue:grain ratio from this single source was 1.6. default s.d. for root:AGB.

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

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

[j] This is the average above-ground biomass reported as litter or harvest losses. This does not include reported stubble, which averaged 0.165 x 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_{SOM}) [15]

The term F_{SOM} 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_2O (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_1) 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_2O 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_2O 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 ($\Delta C_{Mineral,\ LU}$) for the area, over the inventory period, using Equation 2.25 in Chapter 2. Using the Tier 1 approach, the value for $\Delta C_{Mineral,\ LU}$ will have a single value for all land-uses and management systems. Using Tier 2, the value for $\Delta C_{Mineral,\ LU}$ 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_{SOM}), 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)

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

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

$\Delta C_{Mineral,\ LU}$ = average annual loss of soil carbon for each land-use type (*LU*), tonnes C (Note: for Tier 1, $\Delta C_{mineral,\ LU}$ will have a single value for all land-uses and management systems. Using Tier 2 the value for $\Delta C_{mineral,\ LU}$ 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 [16]. 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

[15] The inclusion of the term F_{SOM} is a change from the previous *1996 IPCC Guidelines*, which did not include the N from mineralisation associated with a loss of soil organic C.

[16] 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 Tier 1, the value for F_{SOM} is calculated in a single step. For Tier 2, 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_2O 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://faostat.fao.org/), and expert advice 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_2O emissions

This section has further elaboration of the methods.

In addition to the direct emissions of N_2O from managed soils that occur through a direct pathway (i.e., directly from the soils to which N is applied), emissions of N_2O also take place through two indirect pathways (i.e., 'off-site' N_2O emission from N deposition and N leaching, as illustrated above in Section 11.2).

The first of these pathways is the volatilisation of N as NH_3 and oxides of N (NO_x), and the deposition of these gases and their products NH_4^+ and NO_3^- onto soils and the surface of lakes and other waters. The sources of N as NH_3 and NO_x 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_2O emissions in an exactly analogous way to those resulting from deposition of agriculturally derived NH_3 and NO_x, 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 [17], 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_3^- 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_3^- 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_4^+ and NO_3^- to N_2O. 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_2O 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 [18], 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});
- N in crop residues (above- and below-ground), including N-fixing crops and forage/pasture renewal returned to soils (F_{CR}) [19]; and

[17] Crop residues should be included as an N input into the leaching and runoff component.

[18] Volatilisation and subsequent deposition of nitrogen from the manure in manure management systems is covered in the manure management section of this Volume.

[19] Nitrogen from these components is only included in the leaching/run-off component of indirect N_2O emission.

- N mineralisation associated with loss of soil organic matter resulting from change of land use or management on mineral soils (F_{SOM}) [18].

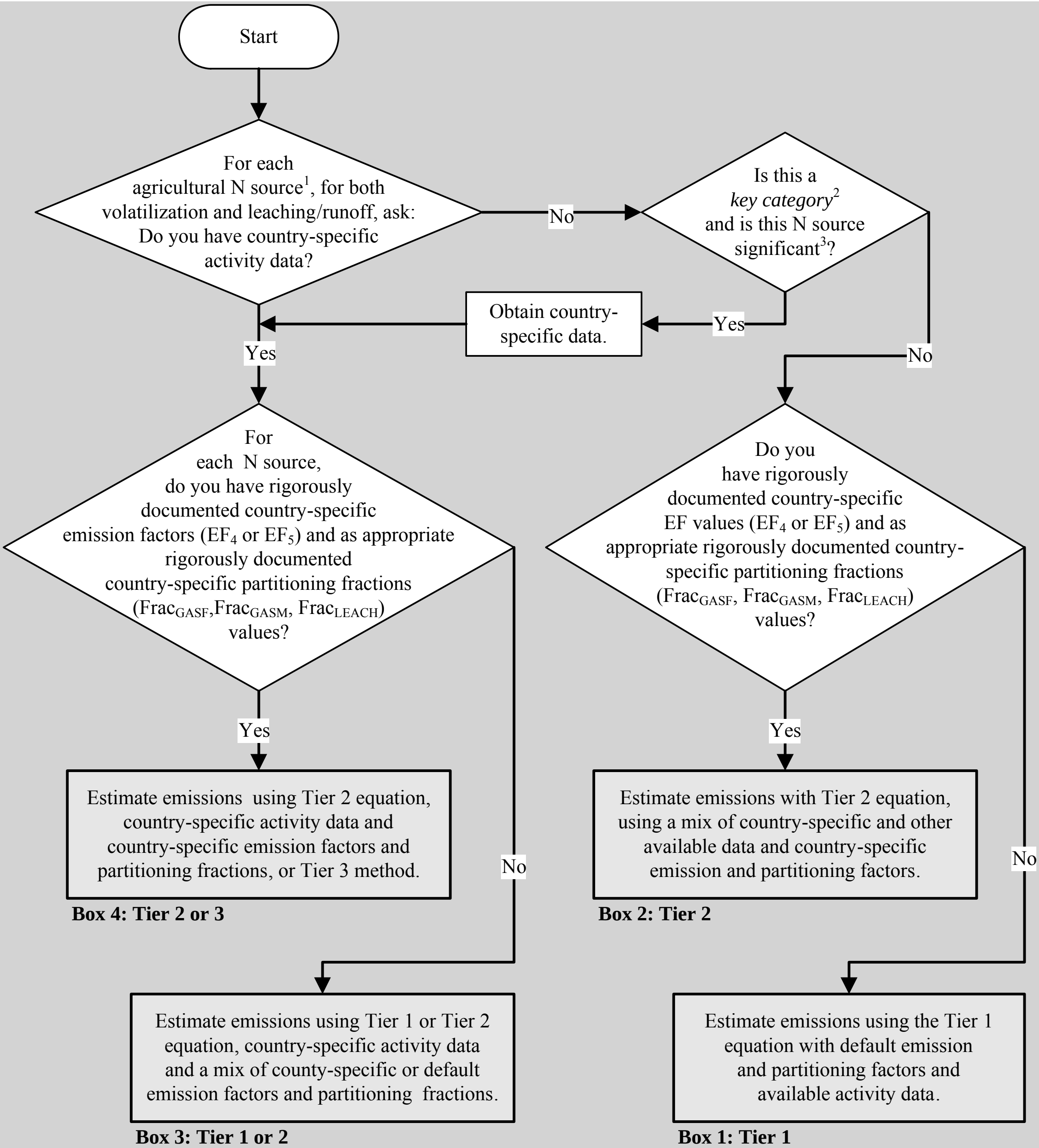
The generic Tier 1 and Tier 2 methods described below can be used to estimate aggregate total indirect N_2O emissions from agricultural N additions to managed soils for an entire country. If a country is estimating its direct N_2O from managed soils by land-use category, the indirect N_2O emissions can 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_2O emissions from combustion-related and industrial sources is described in Volume 1, Chapter 7, Section 7.3.

11.2.2.1 CHOICE OF METHOD

This section is updated with new guidance.

Refer to the decision tree in Figure 11.3 (Indirect N_2O Emissions) for guidance on which Tier method to use.

Figure 11.3 Decision tree for indirect N_2O 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_2O 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.

Tier 1

Volatilisation, $N_2O_{(ATD)}$

The N_2O emissions from atmospheric deposition of N volatilised from managed soil are estimated using Equation 11.9:

EQUATION 11.9
N_2O FROM ATMOSPHERIC DEPOSITION OF N VOLATILISED FROM MANAGED SOILS (TIER 1)

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

Where:

$N_2O_{(ATD)}$–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilised from managed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertiliser N applied to soils, kg N yr^{-1}

$Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x, kg N volatilised (kg of N applied)$^{-1}$ (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^{-1}

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

$Frac_{GASM}$ = 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_3 and NO_x, kg N volatilised (kg of N applied or deposited)$^{-1}$ (Table 11.3)

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$] (Table 11.3)

Conversion of $N_2O_{(ATD)}$-N emissions to N_2O emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(ATD)} = N_2O_{(ATD)} \text{–}N \bullet 44/28$$

Leaching/Runoff, $N_2O_{(L)}$

The N_2O emissions from leaching and runoff in regions where leaching and runoff occurs are estimated using Equation 11.10:

EQUATION 11.10
N_2O FROM N LEACHING/RUNOFF FROM MANAGED SOILS IN REGIONS WHERE LEACHING/RUNOFF OCCURS (TIER 1)

$$N_2O_{(L)}\text{–}N = \left(F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}\right) \bullet Frac_{LEACH-(H)} \bullet EF_5$$

Where:

$N_2O_{(L)}$–N = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertiliser N applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}

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^{-1}

F_{PRP} = annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs, kg N yr^{-1} (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^{-1}

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^{-1} (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)$^{-1}$ (Table 11.3)

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$ (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 $N_2O_{(L)}$–N emissions to N_2O emissions for reporting purposes is performed by using the following equation:

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

Tier 2

If more detailed emission, volatilisation or leaching factors are available to a country than are presented in Table 11.4, 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 [20]:

EQUATION 11.11

N_2O FROM ATMOSPHERIC DEPOSITION OF N VOLATILISED FROM MANAGED SOILS (TIER 2)

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

Where:

$N_2O_{(ATD)}$–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilised from managed soils, kg N_2O–N yr^{-1}

F_{SNi} = annual amount of synthetic fertiliser N applied to soils under different conditions *i*, kg N yr^{-1}

$Frac_{GASF_i}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x under different conditions *i*, kg N volatilised (kg of N applied)$^{-1}$

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr^{-1}

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

$Frac_{GASM}$ = 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_3 and NO_x, kg N volatilised (kg of N applied or deposited)$^{-1}$ (Table 11.3)

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilised)$^{-1}$] (Table 11.3)

Note: If a country is able to estimate the quantity of N mineralised from drainage/management of organic soils then include this as one of the N inputs into the Tier 2 modification of Equation 11.10. Countries can also develop emission factors for FracGASF and FracGASM that are specific for mitigation options such as the application of urease inhibitors.

Conversion of $N_2O_{(ATD)}$–N emissions to $N_2O_{(ATD)}$ emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(ATD)} = N_2O_{(ATD)}\text{–}N \bullet 44/28$$

According to Equations 11.1, 11.10 and 11.11, direct and indirect emissions of N_2O from managed soils are calculated in the Tier 1 approach on the basis of total N from animal manure applied to soils. As noted in Section

[20] 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.

11.2.1.1, the processes of run-off of N, volatilization of NH_3 and NOx, emissions of N_2O, and leaching of N, however, do not occur simultaneously but in a sequence, with the peak of run-off and NH_3+NOx volatilization happening before emissions of N_2O and losses of N through leaching. For example, an application technique affecting the volatilization rate of NH_3+NO_x is likely to change the flow rates of subsequent processes. To illustrate, injecting slurry instead of broadcasting increases the availability of N for N_2O emissions and N-leaching. It is therefore good practice to carefully assess such 'pollution swapping' effects when implementing higher Tier approaches and adopt the N-flow principle when estimating direct N_2O emissions and indirect N_2O emissions from leaching and runoff. This can be done by accounting for the increased pool of nitrogen which is available for direct N_2O emissions and nitrogen leaching.

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 Accounting System.

11.2.2.2 CHOICE OF EMISSION, VOLATILISATION AND LEACHING FACTORS

This section is updated with new emission factors.

The method for estimating indirect N_2O 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 or in dry climates regions where irrigation (other than drip irrigation) is used, the default $Frac_{LEACH-(H)}$ is 0.32. For dry climates, where precipitation is lower than evapotranspiration throughout most of the year and leaching is unlikely to occur, the default $Frac_{LEACH}$ is zero. The method of calculating whether $Frac_{LEACH-(H)}$ = 0.32 should be applied is given 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_2O 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_2O 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_2O emissions resulting from inputs to managed soils to the country of origin of the atmospheric NO_x and NH_3, rather than the country to which the atmospheric N may have been transported.

11.2.2.3 CHOICE OF ACTIVITY DATA

This section is updated with an alternative method for estimating crop residues.

In order to estimate indirect N_2O emissions from the various N additions to managed soils, the parameters F_{SN}, F_{ON}, F_{PRP}, F_{CR}, F_{SOM} need to be estimated.

Applied synthetic fertiliser (F_{SN})

The term F_{SN} refers to the annual amount of synthetic fertiliser N applied to soils. Refer to the activity data section on direct N_2O emissions from managed soils (Section 11.2.1.3) and obtain the value for F_{SN}.

Applied organic N fertilisers (F_{ON})

The term F_{ON} refers to the amount of organic N fertiliser materials intentionally applied to soils. Refer to the activity data section on direct N_2O emissions from managed soils (Section 11.2.1.3) and obtain the value for F_{ON}.

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

The term F_{PRP} 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_2O emissions from managed soils (Section 11.2.1.3) and obtain the value for F_{PRP}.

Crop residue N, including N from N-fixing crops and forage/pasture renewal, returned to soils (F_{CR})

The term F_{CR} 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_2O emissions from managed soils (Section 11.2.1.3) and obtain the value for F_{CR}.

UPDATED TABLE 11.3
DEFAULT EMISSION, VOLATILISATION AND LEACHING FACTORS FOR INDIRECT SOIL N_2O EMISSIONS

	Aggregated		**Disaggregated**		
Emission factor	**Default value**	**Uncertainty range**	**Disaggregation**	**Default value**	**Uncertainty range**
EF_4 [N volatilisation and re-deposition], kg N2O–N (kg NH3–N + NOX–N volatilised)-1	0.010	0.000 – 0.002	Wet climate	0.015	0.012 – 0.019
			Dry climate	0.005	0.000 – 0.012
EF_5 [leaching/runoff], kg N2O–N (kg N leaching/runoff) -1	0.011	0.000 – 0.031	-	-	-
FracGASF [Volatilisation from synthetic fertiliser], (kg NH3–N + NOx–N) (kg N applied) –1	0.112	0.020 – 0.330	Urea	0.153	0.030 – 0.430
			Ammonium-based	0.091	0.020 – 0.300
			Nitrate-based	0.010	0.000 – 0.020
			Ammonium-nitrate-based	0.059	0.001 – 0.200
FracGASM [Volatilisation from all organic N fertilisers applied, and dung and urine deposited by grazing animals], (kg NH3–N + NOx–N) (kg N applied or deposited) –1	0.110	0.000 – 0.423	-	-	-
FracLEACH-(H) [N losses by leaching/runoff for regions where Σ(rain in rainy season) - Σ (PE in same period) > soil water holding capacity, OR where irrigation (except drip irrigation) is employed], kg N (kg N additions or deposition by grazing animals)$^{-1}$	0.236	0.011 – 0.733	-	-	-

Notes: The FracLEACH-(H) only applies to regions where soil water-holding capacity is exceeded, as a result of rainfall and/or irrigation (excluding drip irrigation), and leaching/runoff occurs. In the definition of FracLEACH-(H) above, PE is potential evaporation, and the rainy season(s) can be taken as the period(s) when rainfall > 0.5 * Pan Evaporation. (Explanations of potential and pan evaporation are available in standard meteorological and agricultural texts). For other regions the default FracLEACH is taken as zero. Precipitation and potential evapotranspiration data is 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.

EF_4: The aggregated EF_4 is the same as the aggregated EF_1 (see Annex 11A.5). Disaggregation by climate: Wet climate relates to temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climate relates to temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm (cf. Chapter 3 of Vol. 4.). Uncertainty range of disaggregated EF_4 based on the 95% confidence interval of fitted values (See methods and data in Annex 11A.5)
EF_5: This emission factor incorporates three components: EF_{5g}, EF_{5r} and EF_{5e}, which are the emission factors for groundwater and surface drainage, including upstream supersaturated with N_2O (N_2O emitted mainly from degas of groundwater), rivers and reservoirs, including downstream (supersaturated N_2O was already degassed and N_2O mainly produced by nitrification/denitrification in situ), and estuaries, respectively. EF5g: 0.006 kg N_2O–N/kg NO_3-N in the water, EF_{5r}: 0.003 kg N_2O–N/kg NO_3-N in the water and EF5e: 0.002 kg N_2O–N/kg NO_3-N in the water, based on Cai et al. (2018) (see Annex 11A.6). Uncertainty range based on the 2.5th to 97.5th percentile.
FracGASF : Calculated by weighting world fertiliser usage with number of observations from review papers by Bouwman et al. (2002) and Pan et al. (2006) for NH_3 and Liu et al. (2017) for NO_x (See methods and data in Annex 11A.7). Uncertainty range based on the 2.5th to 97.5th percentile.
FracGASM: See methods in Annex 11A.8. Uncertainty range based on the 2.5th to 97.5th percentile.
FracLEACH-(H): See methods in Annex 11A.9. Uncertainty range based on the 2.5th to 97.5th percentile.

Mineralised N resulting from loss of soil organic C stocks in mineral soils (F_{SOM})

The term F_{SOM} 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_2O emissions from managed soils (Section 11.2.1.3) and obtain the value for F_{SOM}.

11.2.2.4 UNCERTAINTY ASSESSMENT

No Refinement

11.2.3 Completeness, Time series, QA/QC

No refinement

11.3 CO2 EMISSIONS FROM LIMING

No refinement

11.4 CO2 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_1

Material and methods

We extracted all studies from the databases by Albanito et al. (2017), Cayuela et al. (2017), Liu et al. (2017), Stehfest and Bouwman (2006), Rochette et al. (2018), and van Lent et al. (2015) 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_{1FR}),
- Related to grazed soils where urine and/or dung was applied (emissions from urine/dung inputs in grazed soils are estimated using the EF_{3PRP}),
- Related to enhanced synthetic or organic fertiliser either treated with inhibitors or coated, and
- Were conducted on drained organic soils.

The resulting merged database contained 1999 cases reporting soil fluxes of N_2O on mineral soils from unfertilized natural sites and from anthropogenically modified sites, either fertilized or unfertilized. Climate (Temperate/Boreal Wet, Temperate/Boreal, Dry Tropical Wet, Tropical Dry) could be assigned to 1978 cases. Wet climates relate to temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration > 1, and tropical zones where annual precipitation > 1000 mm. Dry climates relate to temperate and boreal zones where the ratio of annual precipitation: potential evapotranspiration < 1, and tropical zones where annual precipitation < 1000 mm. Temperate, boreal and tropical zones correspond to those defined in Chapter 3 of Vol. 4 in the 2006 IPCC guidelines. 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 form comprised two groups: organic and synthetic plus mixed.

Two generic methods were tested to develop the aggregated and disaggregated emission factors: By regression analysis of N_2O emission against N input and by linear mixed-effect model analysis of individual EF_{1i} cases. The EF_{1i} was computed using a control site as:

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

Where N_2O_{Ti} is the N_2O flux during the experimental period due to the application of inputs N_i and other unquantified sources of N; and N_2O_{Ci} is the N_2O flux during the experimental period at a control site due to other sources of N than N_i.

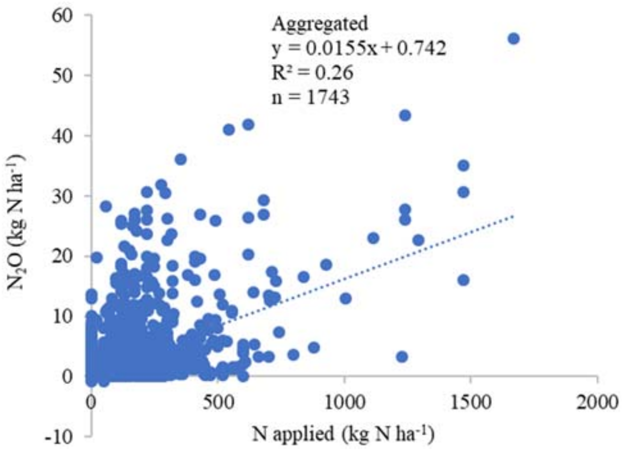
The linear mixed-effect model approach was selected to account for lack of independence among observations from the site as a random effect. For this a location identification was assigned to all individual cases. Cases with an identical coordinate or from a same reference with a same soil type and land use were considered a unique location. Climate, fertiliser and their interaction were treated as fixed-effects. Influence of the length of the experiment as well as influence of irrigation in dry climates were also evaluated by considering these two variables as a fixed-effects. Means for the fixed-effects were compared using the LSD Fisher test. The 95% confidence interval (CI) of fitted values by the models was considered for uncertainty quantification of disaggregated EF_1. Given the unbalance of the dataset between climates and fertiliser forms (75% in wet climate, 75% with synthetic plus mixed fertiliser forms), the aggregated EF_1 was computed as the average of disaggregated EF_1. The low and high uncertainty values of the aggregated EF_1 were assigned the lowest and highest value of the 95% CI from disaggregated EF_1. The low uncertainty value was truncated at zero to avoid a negative value.

The linear mixed-effect model analysis was performed on the entire dataset of observations from anthropogenically modified treatments (i.e., modification of the N input). The fixed-effects in the linear mixed-effect models were used to disaggregate emission factors. The coefficient of determination and the significance of the slope were evaluated and assumptions regarding a normal distribution of the error and equality of variance were tested.

Results

None of the linear regressions met the assumption of equality of variance. The dataset was skewed with a strong influence exerted by the cases fertilised at a rate > 200 kg N ha-1 on the slope of the regression (Figure A2-1). Log-transformation of the variables did not lead to homoscedasticity. Therefore, this method was discarded, as mentioned above.

Figure A2-1: Linear regression of N_2O emission against N input.



The linear mixed-effect model analysis indicated no clear trend of decrease or increase of the EF_1 according to the length of the experimental period (Table A2-1). Therefore, this criterion was not considered further in the analysis.

TABLE A2-1
SAMPLE SIZE, MEAN, AND LOW AND HIGH UNCERTAINTIES OF THE EF1 DISAGGREGATED BY LENGTH OF THE EXPERIMENT. A, B LETTERS INDICATE A SIGNIFICANT DIFFERENCE BETWEEN MEANS.

Disaggregation by length of experiment	n	Mean	Low	High	Significance
≤120 days	312	0.0128	0.009	0.0176	B
120 < days ≤ 180	179	0.0213	0.017	0.0269	C
180 < days ≤ 240	81	0.0092	0.003	0.0158	B
240 < days ≤ 300	40	-0.001	-0.010	0.008	A
>300 days	203	0.0137	0.009	0.0184	B

The analysis yielded no significant difference in EF_1 between the four climates as disaggregated by temperature and rainfall (Table A2-2). However, disaggregation by moisture regimes alone did lead to significant differences in the EF_1 factors with higher values for wet climates than for dry climates. In dry climate, irrigation practice was indicated in 76% of the cases, of which the majority (63%) were irrigated. The EF_1 was significantly higher when irrigation was practiced. Given that the EF_1 when the land was irrigated (0.004, n = 94) was close to the EF_1 for dry climates (0.005, n = 198), and that most sites in dry climate were irrigated, irrigation practice was not included as a criterion for disaggregation of EF_1.

Comparison between the three fertiliser forms (S: Synthetic, O: Organic, M: Mixed S+O) suggested that synthetic and mixtures of synthetic and organic forms were not significantly different and could be grouped into a single category. The EF_1 obtained from the interaction of climate disaggregated by rainfall and fertiliser with two levels of disaggregation were similar in dry climates. In wet climate the EF_1 of the S + M form was significantly higher than the EF_1 of the organic fertilisers.

Based on these results, the EF_1 was disaggregated by climate and fertiliser with no distinction between fertiliser form in dry climate, but with a distinction between organic fertiliser and synthetic plus mixed fertiliser in wet climate. As activity data distinguish applied synthetic N fertiliser from applied organic N fertiliser, the category synthetic plus mixed fertiliser was simplified to synthetic fertiliser.

TABLE A2-2
SAMPLE SIZE, MEAN, AND LOW AND HIGH UNCERTAINTIES OF THE EF1 DISAGGREGATED BY CLIMATE, FERTILISER FORM AND IRRIGATION PRACTICE. A, B LETTERS INDICATE A SIGNIFICANT DIFFERENCE BETWEEN MEANS WITHIN A DISAGGREGATION LEVEL BASED ON LSD FISHER TEST

Disaggregation by climate (temperature, rainfall)	**n**	**Mean**	**Low**	**High**	**Significance**
temperate/boreal wet	498	0.016	0.012	0.020	B
temperate/boreal dry	121	0.007	-0.002	0.016	A B
tropical wet	122	0.013	0.007	0.019	A B
tropical dry	77	0.004	-0.006	0.013	A A
Disaggregation by climate (rainfall)	n	Mean	Low	High	
wet	620	0.015	0.012	0.019	B
dry	198	0.005	-0.001	0.012	A
Disaggregation by irrigation in dry climate	n				
Irrigation	94	0.004	0.0025	0.006	B
No irrigation	56	0.001	-0.001	0.003	A
Disaggregation by fertiliser form (S: Synthetic, O: Organic, M: Mixed S+O)	n	Mean	Low	High	
O	139	0.008	0.004	0.013	A
M	57	0.015	0.009	0.021	B
S	586	0.015	0.011	0.018	B
Disaggregation by climate (rainfall) and fertiliser form (S + M: Synthetic and Mixed S+O, O: Organic)	n	Mean	Low	High	
wet O	86	0.007	0.001	0.013	A
wet S + M	505	0.017	0.013	0.020	B
dry O	53	0.005	-0.004	0.013	A
dry S + M	138	0.005	-0.002	0.012	A

Sources of Data

Albanito, F., Lebender, U., Cornulier, T., Sapkota, T.B., Brentrup, F., Stirling, C., Hillier, J., 2017. Direct nitrous oxide emissions from tropical and sub-tropical agricultural systems - A review and modelling of emission factors. Scientific reports 7:44235 | DOI: 10.1038/srep44235.

Cayuela, M.L., Aguilera, E., Sanz-Cobena. A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., Lassaletta, L., 2017. Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. . Agric Ecosyst Environ. 238, 25-35.

Liu, S., Lin, F., Wu, S., Cheng, J., Sun, Y., Jin, Y., Li, S., Li, Z., Zou, J., 2017. A meta-analysis of fertilizer-induced soil NO and combined with N2O emissions. . Global Change Biol. 23, 2520-2532.

Rochette, P., Liang, B.C., Pelster, D., Bergeron, O., Lemke, R., Kroebel, R., MacDonald, D., Yan, W., Flemming, C., 2018. Soil nitrous oxide emissions from agricultural soils in Canada: exploring relationships with soil, crop and climatic variables. Agriculture, Ecosystems and Environment 254, 69-81.

Stehfest, E., Bouwman, L., 2006. N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutrient Cycling in Agroecosystems 74, 207-228.

van Lent, J., Hergoualc'h, K., Verchot, L.V., 2015. Soil N2O and NO emissions from land use and land-use change in the tropics and subtropics: a meta-analysis. Biogeosciences 12, 7299-7313.

Annex 11A.3 Estimation of Default Emission Factor(s) for EF_{1FR}

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_{1FR} values and the arithmetic mean was 0.4%. Water management strongly affects N_2O emission from paddy rice fields (Akiyama et al., 2005). Therefore, aggregated and disaggregated values by water management were calculated based arithmetic means and confidence intervals were constructed to include 95% of the distribution of measured emissions. Arithmetic mean of 'continuous flooding' (0.3%, n = 44) was lower than 'with single and multiple drainage' based on these data (0.5%, n = 26).

Sources of data

Akiyama et al., 2005. Direct N2O emission from rice paddy fields: Summary of available data. Glob. Biogeochem. Cycles, 19(1), art. no. GB1005.

Albanito, F., Lebender, U., Cornulier, T., Sapkota, T.B., Brentrup, F., Stirling, C., Hillier, J., 2017. Direct nitrous oxide emissions from tropical and sub-tropical agricultural systems - A review and modelling of emission factors. Scientific reports 7:44235 | DOI: 10.1038/srep44235.

Cayuela, M.L., Aguilera, E., Sanz-Cobena. A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., Lassaletta, L., 2017. Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. . Agric Ecosyst Environ. 238, 25-35.

Annex 11A.4 Estimation of Default Emission Factor(s) for EF_{3PRP}

We combined the dataset recently collated by Cai & Akiyama (2016) with 27 additional studies to derive EF_{3PRP} factors (see reference list). 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_{3PRP} values, with urine dominating the data, representing 326 (=71%) of the values. Data was 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_2O production and emission from urine patches (de Klein et al. 2003; van der Weerden et al. 2014). Therefore, EF_{3PRP} data has been disaggregated by climate (dry and wet) for countries 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 is currently insufficient observations in the dataset to allow further climate disaggregation. Aggregated values are also provided for countries that are not able to disaggregate PRP N inputs by climate.

The data was analysed using a linear model, with excreta type (dung vs. urine vs. artificial urine), livestock type (cattle vs. sheep), land use (pastoral vs. forage crop) and climate (wet vs. dry) 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 $a = 0.25\%$). 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_{3PRP} values ($P = 0.05$). However, given most sites used either real urine or artificial urine, but not both types, further analysis was conducted where data was limited to sites where both urine types were used to determine if the differences were due to site variation or the type of urine (de Klein et al. 2003; Chadwick et al. 2018). This direct comparison showed urine type had no significant effect on EF_{3PRP} ($P = 0.88$, $n=16$). On this basis, all artificial urine data were included, adding considerably more observations in the dataset.

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_{3PRP} values for cattle and sheep dung and urine, in wet and dry climates are shown in Table A4-1

TABLE A4-1
EF VALUES FOR CATTLE AND SHEEP DUNG AND URINE, IN WET AND DRY CLIMATES

Livestock type	Excreta type	Climate			
		Wet		Dry	
		mean	2.5th to 97.5th percentile, n	mean	2.5th to 97.5th percentile, n
Cattle	Urine	0.0077	0.0003 – 0.0382, 279	0.0033	0.0003 – 0.0094, 10
	Dung	0.0013	0.0000 – 0.0043, 24	0.0007	0.0001 – 0.0012, 6
Sheep	Urine	0.0039	0.0004 – 0.0180, 35	0.0027[A]	See [A] below
	Dung	0.0004	0.0000 – 0.0027, 21	0.0008[B]	See [B] below

A This value is based on only two data, however it is considered to be a reasonable estimate given the cattle urine values for wet and dry climates. Therefore, this value for sheep urine in dry climates has been retained.

B The dataset contained a single data value for sheep dung in dry climates (1.04%); this single value was considered to be non-representative of the source, given the dung values for other sources. Therefore, a value for sheep dung in dry climates was estimated by calculating the mean of dung values for sheep in dry climates, cattle in dry climates and cattle in wet climates.

Disaggregated excreta EF_{3PRP} values for cattle in wet and dry climates and sheep in wet and dry climates (Table 11.1) were calculated from the urine and dung EF_{3PRP} values reported in Table 11A.1, assuming a urine:dung ratio of 0.66:0.34 (Kelliher et al. 2014). However, countries may wish to 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.

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Annex 11A.5 Estimation of Default Emission Factor(s) for EF_4

In order to develop EF_4 values, review papers on indirect N_2O 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_2O 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_2O emissions from the zero-N control (N_2O from N mineralization, plant litter and N deposition) could be removed by subtracting the associated emissions from the treatment plots. The EF was computed as:

$$EF\ (\%) = (N_2O_{\text{N treatment}} - N_2O_{\text{control}}) / \text{N input} \times 100$$

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 similar to the EF_1 values estimated for this report (Table A5-1), at least given that most of experiments relevant for estimating new EF_4 factors were conducted on temperate wet climate zones.

TABLE A5-1

RESULTS FROM REVIEW PAPERS OF N ADDITION EXPERIMENTS IN NON-AGRICULTURAL SITES

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_2O emission and N deposition on conducted in non-agricultural sites

In these experiments N_2O emission and N deposition were measured concurrently in non-agricultural and non-wetland sites, and the EF was calculated as follows:

$$EF\ (\%) = N_2O / \text{N deposition} \times 100$$

The advantage of this type of study is that actual N deposition rates were measured at these sites. However, the disadvantage is that EF do not exclude N_2O from a zero-N control (N_2O from N mineralization), and therefore the influence of N deposition could not be isolated from other sources of N_2O emissions. In general, the EF values of these studies were higher than those from N addition experiments in non-agricultural sites (Table A5-2), probably because the resulting EFs did not exclude N_2O from N mineralization 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_2O emissions.

TABLE A5-2

RESULTS FROM REVIEW PAPERS OF N_2O EMISSIONS AND N DEPOSITION CONDUCTED AT NON-AGRICULTURAL SITES

References	n	Mean EF (%)	SD	Note
Buhlman et al., 2015	57	7.0	8.7	Mean was calculated from Table S1.
Denier van der Gon & Bleeker 2005	21	3.8	4.1	Weighted mean was calculated from Table 3.
DeVries et al., 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_1 results from our analysis, we decided to use the same emission factors as EF_1 for EF_4. Notwithstanding given the absence of dependence of EF_4 upon the form (organic or synthetic) of original N input that volatised, disaggregation only by climate was considered. The EF_4 was disaggregated by wet and dry climates, as indicated in Table A2-1 of Annex11A.2.

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Annex 11A.6 Estimation of Default Emission Factor(s) for EF_5

We collected peer-reviewed papers, and included data observations that were in situ field studies. The final dataset contained 182 data observations (EF_{5g}: n = 82, EF_{5r}: n = 79, EF_{5e}: n = 21).

The EF_{5g}, EF_{5r} and EF_{5e} are defined as:

EF_{5g}: groundwater (soil solution and lysimeter leaching water were not included), spring, surface drainage, and upstream emissions (upstream supersaturated with N_2O, N_2O emitted mainly from degas of groundwater)

EF_{5r}: rivers, reservoirs (including lake and pond), and downstream emissions (supersaturated N_2O was already degassed and N_2O mainly produced by nitrification/denitrification in situ).

EF_{5e}: 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 some confusion in dividing EF_{5g} and EF_{5r} for streams, at least in some studies. Here, we categorized data into EF_{5g} based on upstream supersaturated with N_2O where N_2O is emitted mainly from degassing of groundwater, and EF_{5r} based on downstream, supersaturated N_2O that was already degassed and N_2O 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 hard to separate the different N sources based on the limited information in the publications. Therefore, our dataset on EF_{5r} includes non-agriculture N source.

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

Arithmetic mean emission factors were calculated as follows; EF_{5g}: 0.0055 kg N_2O–N/kg NO_3-N in the water, EF_{5r}: 0.0027 kg N_2O–N/kg NO_3-N in the water and EF_{5e}: 0.0023 kg N_2O–N/kg NO_3-N in the water. Uncertainties were based on 95% confidence intervals given the data distribution that was collected from the published studies.

Source of data

Cai Y, Tian L and Akiyama H, 2018, A review of indirect N_2O emission factors from agricultural nitrogen leaching and runoff to update of the default IPCC values, submitted.

Annex 11A.7 Estimation of Default Emission Factor(s) for $Frac_{GASF}$

The Tier 1 aggregated default NH_3 + NO_x 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 A7-1), based on world fertiliser usage. For countries that require inventories for air pollutant emissions, there is a continuous update of NH_3 and NO EF values through the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2016).

TABLE A7-1
FERTILISER CONSUMPTION IN THE PERIOD 2007-2015 EXPRESSED AS THOUSAND TONNES NUTRIENTS AND % OF TOTAL FERTILISER CONSUMED (SOURCE: IFA: HTTP://IFADATA.FERTILIZER.ORG/)

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%
N P K compound (N)	127227	14%

For disaggregation, we divided all fertiliser usage into 4 types of fertiliser categories based on their basic chemical composition: urea, ammonium-based, nitrate-based and ammonium-nitrate-based. 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 A7-2).

TABLE A7-2
ASSUMPTIONS ON THE POTENTIAL MIX OF DIFFERENT IFA FERTILISER PRODUCTS

Fertiliser product	Fertiliser Mix
Ammonia (direct application)	AS, DAP and MAP
Nitrogen solutions	AN, CAN
Other N straight	urea, AS, AN, CAN, DAP, MAP, nitrate-based, UAN
Other NP (N)	urea, AS, AN, CAN, DAP, MAP, nitrate-based, UAN
N K compound (N)	Nitrate-based
N P K compound (N)	AS, AN, CAN, DAP, MAP, UAN

For NH_3, 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_3 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_x, we used the dataset of peer-reviewed studies collated by Liu et al. (2017). For the Tier1 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_x EFs, we estimated values that were specific to different fertiliser types.

Median EF values for each fertiliser type for both NH_3 and NO_x are shown in Table A7-3.

TABLE A7-3
EMISSION FACTORS FOR % NH_3–N AND NO_x-N (N APPLIED) $^{-1}$) FROM DIFFERENT FERTILISER TYPES RESULTING FROM TWO META-ANALYSIS AND NUMBER OF STUDIES INVOLVED

	% lost as N				number of studies		
Fertiliser	**Total**	**NH3-N**	**NOx-N**		**Total**	**NH3-N**	**NOx-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	12.1%	9.1%	3.0%		11	8	3
MAP	6.3%	5.3%	1.0%		3	2	1
nitrate	1.2%	0.2%	1.0%		4	1	3
UAN	9.6%	9.4%	0.2%		11	9	2

EF values for NH_3 emissions were compared with those obtained using the method to predict NH_3 emissions in the current EMEP/EEA guidelines (Hutchins et al., pers. comm.) and were comparable to the range calculated by Hutchins (*pers. commun*.).

Sources of data

Meta-analysis (references for individual studies can be obtained from Bowman et al., 2002; Pan et al., 2016 and Liu et al., 2017)

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Estimation of global NH3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. Global Biogeochem. Cycles 16, 8–1. https://doi.org/10.1029/2000GB001389

European Environment Agency, 2016. EMEP/EEA air pollutant emission inventory guidebook 2016. Technical guidance to prepare national emission inventories. Publications Office of the European Union, Luxembourg. 24 pp. ISBN 978-92-9213-806-6. doi:10.2800/247535

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Annex 11A.8 Estimation of Default Emission Factor(s) for $Frac_{GASM}$

Review papers on NH_3 and NO were collected to derive the fraction of N that is volatilized. Field measurement data with manure application and excreta patches were extracted from the published literature (see below). Field measurement data with chemical N application were excluded from this analysis, as well as studies with a focus on mitigation technologies, such as nitrification inhibitors.

For NH_3, the arithmetic mean and uncertainty range for 95% confidence intervals were calculated from Cai & Akiyama (2016). For NO, the mean and uncertainty range were calculated from Cai and Akiyama (2016) and Liu et al., (2017). The difference between mean EF for cattle and sheep excreta were negligible, thus livestock type was not considered. The sum of NH_3 and NO is 11%, and the uncertainty range was calculated using equation 3.2 in the 2006 IPCC guidelines Vol. 1 Chapter 3.

Sources of data

Cai, Y., Akiyama, H., 2016. Nitrogen loss factors of nitrogen trace gas emissions and leaching from excreta patches in grassland ecosystems: A summary of available data. Science of the Total Environment 572, 185-195.

Liu, S., Lin, F., Wu, S., Cheng, J., Sun, Y., Jin, Y., Li, S., Li, Z., Zou, J., 2017. A meta-analysis of fertilizer-induced soil NO and combined with N_2O emissions. Global Change Biol. 23, 2520-2532.

Annex 11A.9 Estimation of Default Emission Factor(s) for $Frac_{LEACH-(H)}$

We collected review papers and original research on N leaching for this analysis. Only peer-reviewed papers that used lysmeter field 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. The arithmetic mean and uncertainty range for a 95% confidence interval were calculated from the dataset.

Sources of data

Reviews (Datasets are in the reviews):

Cai, Y., Akiyama, H., 2016. Nitrogen loss factors of nitrogen trace gas emissions and leaching from excreta patches in grassland ecosystems: A summary of available data. Science of the Total Environment 572, 185-195.

Di and Cameron, 2002, Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies, Nutrient Cycling in Agroecosystems 46, 237–256.

Original papers:

Aronsson H, Stenberg M (2010) Leaching of nitrogen from a 3-yr grain crop rotation on a clay soil. Soil Use Manag **26**, 274–285.

Asadi ME, Clemente RS, Das Gupta A, Loof R, Hansen GK (2002) Impacts of fertigation via sprinkler irrigation on nitrate leaching and corn yield in an acid-sulphate soil in Thailand. Agric Water Manag **52**,197–213.

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