Category		Title
NFR	3.D	Crop production and agricultural soils
	3.D.a.1,	Inorganic N fertilisers (includes urea);
	3.D.a.2.a,	Livestock manure applied to soils;
	3.D.a.2.b,	Sewage sludge applied to soils;
	3.D.a.2.c	Other organic fertilisers applied to soils (including compost);
	3.D.a.3,	Urine and dung deposited by grazing livestock;
	3.D.a.4,	Crop residues applied to soils*;
	3.D.b,	Indirect emissions from managed soils; Farm-level agricultural operations including storage, handling and transport of agricultural products;
	3.D.c,	Off-farm storage, handling and transport of bulk agricultural
	3.D.d,	products;
	3.D.e	Cultivated crops
	3.D.f	Use of pesticides
	3F	Field burning of agricultural residue
SNAP	The Nomenclature for Reporting (NFR) codes do not readily equate to the previous SNAP codes. This chapter provides guidance on the calculation of emissions previously reported under the following SNAP codes	
	100101	Permanent crops
	100102	Arable land crops
	100103	Rice field
	100104	Market gardening
	100105	Grassland
	100101	Fallows
ISIC		
Version	Guidebook 2023	

* The official nomenclature is misleading as the reporting category not only includes residues actively applied to soils from outside the field, e.g. for the purposes of erosion control or mulching, but also crop residues that are left on the soil surface after harvest and returned to soil by weathering and cultivation.

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1 Overview

Inventories of emissions are required for three purposes:

- to provide annual updates of total emissions in order to assess compliance with agreed commitments;
- to identify the main sources of emissions in order to formulate approaches to make the most effective reductions in emissions;
- to provide data for models of air quality dispersion and the impacts of the emissions.

The guidance in this guidebook primarily aims to enable countries to prepare annual national inventories for regulatory purposes. The results obtained using the methods outlined here may also be suitable for some modelling purposes, e.g. the production of abatement cost curves. However, note the current lack of disaggregation at both the temporal and geographical scales, and the limited extent to which the methods take account of the impacts of climate and weather on emissions. This limited account of the impacts of climate and weather is a result mainly of the difficulty in obtaining activity data that are sufficiently detailed in time and space. If possible, users should develop methods to take account of the influence of these factors, if more detailed activity data are available to them. This guidebook provides methodologies that use inputs that can be reliably obtained by emission inventory compilers.

Ammonia (NH_3) emissions lead to the acidification and eutrophication of natural ecosystems. NH_3 may also form secondary particulate matter (PM). Nitric oxide (NO) and non-methane volatile organic compounds (NMVOCs) play a role in the formation of ozone (O_3), which, near the surface of the Earth, can have an adverse effect on human health and plant growth. Particulate emissions also have an adverse impact on human health.

This chapter describes methods to estimate the emissions of NH_3, NO, NMVOCs and PM from crop production and agricultural soils. Emissions of NH_3 from livestock manures applied to soils, and from the excreta deposited by grazing animals, are determined by the calculations described in Chapter 3.B, 'Manure management'. This is because the methodologies developed to calculate NH_3 emissions from livestock husbandry treat those emissions as part of a chain of events, so that the impacts of any factors that affect NH_3 emissions at one stage of manure management on subsequent NH_3 emissions may be taken into account (see Annex 1 of Chapter 3.B 'Manure management'). Note however, emissions from livestock manures applied to soils and urine and faeces deposited by grazing animals are reported under 3D (3Da2a and 3Da3, respectively). The two emission terms are calculated separately in Chapter 3B. Emissions following application of mineral nitrogen (N) fertilisers, sewage sludge and other organic wastes (including digestates produced by anaerobic digestion) are calculated in this chapter.

The persistent organic pollutants should be reported under 3.D.f '*Use of pesticides*' or 3.I '*Agriculture other*'; as yet no robust methodology has been developed.

Emissions (principally NH_3) also arise from crop residues and cultivated crops. While a methodology for NH_3 emissions from crop residues is provided, it is not currently possible to provide a robust methodology for cultivated, living crops. This is because living crops can vary over time between being a source of NH_3 and being a sink, depending on the nutritional status of the crop and the concentration of NH_3 in the surrounding air. Within the scope of the Convention, these fluxes are modelled by EMEP MSC-W (https://www.emep.int/mscw/#).

Crop production and agricultural soils typically contribute c. 51 % of the total source strength for European emissions of NH_3 (Table 1.1 below) and c. 11.6 % of NO (Table 1.1), albeit the contributions vary widely among European Union (EU) Member States. Emissions of gaseous N species from crop production and agricultural soils are generally related closely to the amount of fertiliser N applied. Further information on NO is provided in Annex 2 (A2.1).

Crop production and agricultural soils are currently estimated to emit only c. 1 % of total NMVOC emissions (Table 1.1), and therefore do not yet require a methodology for calculation. However, given current uncertainties regarding the magnitude of NMVOC emissions from agricultural crops, some information is given in this chapter, in order to provide background information and a tool to estimate the order of magnitude of these emissions, as well as to highlight current uncertainties.

Particulate emissions are reported in fractions varying from fine PM (smaller than 2.5 µm ($PM_{2.5}$)) to coarse (total suspended particles (TSP)). Emissions from tillage land are currently estimated to account for c. 2 %, c. 6 % and c. 8 % respectively of $PM_{2.5}$, PM_{10} and TSP emissions in the EU, respectively.

This chapter is divided into two separate sections. The first section, the main part of the chapter, provides guidance on methodologies for calculating emissions at the Tier 1 and Tier 2 levels. The second part, the annexes, provides the scientific documentation underlying the Tier 1 and 2 methodologies and guidance for the development of Tier 3 methodologies.

Emissions from the movement of agricultural vehicles on unpaved roads, from the consumption of fuels and emissions due to the input of pesticides are not included here (see relevant chapters under 1A for mobile machinery and 3Df for the use of pesticides). Pollen and other wind-blown particles from cultivated soils that do not arise directly from field operations are considered as natural emissions. Further information on PM is provided in Annex 4.

Table 1-1 Contributions to emissions from crop production and agricultural soils

	NH_3 [a]	NO_x	NMVOC	$PM_{2.5}$	PM_{10}	TSP
Total, Gg a^{-1}	3 441	5 487	6 247	1 189	1 807	3 238
Crop production and agricultural soils, Gg a^{-1}	1 749	638	437	18	185	614
Crop production and agricultural soils, %	50.8	11.6	7.0	1.5	10.2	19.0

Notes: The figures are 2019 estimates for EU-27.
The estimates of NH_3 emissions include those from the application of livestock manures to agricultural soils and during grazing which explains why some values have increases since 2013.
Gg a^{-1}: Gigagrammes per year
Source: https://www.ceip.at/webdab-emission-database/reported-emissiondata

2 Description of sources

The sources to be reported in Chapter 3D are described in Table 2-1. Emissions from some of these sources are likely to be small. Methodologies are provided to enable users to make an estimate of the size and importance of these emissions.

Table 2-1 Codes for the reporting of gaseous emissions from soils and the sources they cover

NFR	Name	Definition and clarification of source	Are emission factors available?
3.D.a.1	Inorganic N fertilisers (includes urea)	Emissions that arise during and after the application of N fertilisers to land. Not emissions arising from the handling of N fertilisers after delivery to the farm but before application to land; these are to be included with emissions during the handling and storage of other dry bulk materials in 3Dc	NH_3 NO PM — no method
3.D.a.2.a	Livestock manure applied to soils	Livestock manure applied to soils. The guidance for calculating these emissions is given in Chapter 3B	NH_3 — yes, calculated in 3B NO
3.D.a.2.b	Sewage sludge applied to soils	Sewage sludge applied to soils	NH_3
3.D.a.2.c	Other organic fertilisers applied to soils (including compost)	Organic fertilisers, other than livestock manures and sewage sludge, applied to soils (including digestate and compost)	NH_3 NO
3.D.a.3	Urine and dung deposited by grazing livestock	Urine and dung deposited by grazing livestock to fields during grazing. The guidance for calculating these emissions is given in Chapter 3B	NH_3 — yes, calculated in 3B
3.D.a.4	Crop residues applied to soils	All non-senesced ([a]) crop residues which are either returned or applied to soils. In the great majority of cases these will be residues from the crop grown in that field which remain on the soil surface. However, in some cases crop residues may be imported to the field in order to control erosion, act as a mulch or a source of nutrients	NH_3
3.D.b	Indirect emissions from managed soils	Emissions resulting from the deposition of N emitted from managed soils	No method
3.D.c	Farm-level agricultural operations including storage, handling and transport of agricultural products	This source includes not only emissions arising from the handling and storage of agricultural products on farms, such as grain, but also emissions during the handling and storage of products produced elsewhere to be used on the farm such as fertilisers and livestock feeds	Soil cultivation and crop harvesting are currently reported to account for 80 % of PM emissions in 3D ([b]) The values for PM do not include emissions from fertiliser, pesticides or from grassland, e.g. hay making
3.D.d	Off-farm storage, handling and transport of bulk agricultural products	Off-farm storage, handling and transport of bulk agricultural products	Any emissions from this source are to be reported here because they would not be reported elsewhere. However, no methodology has yet been developed for these

3.D.e	Cultivated crops	Ammonia emissions arising from standing or 'cultivated' crops. This source is distinct from emissions of NH_3 that arise from the application of fertiliser to crops (which are reported under 3.D.a.1 and 3.D.a.2.a.c)	No method

([a]) See subsection 2.1.1 for the difference between non-senesced and senesced residues.
([b]) Since PM emissions from livestock production arise from buildings, these are calculated and reported in 3.B.

There are four main sources of emissions from crop production and agricultural soils:

- application of N for crops as mineral N fertiliser, livestock manure and organic waste application (NH_3);
- soil microbial processes (NO);
- crop processes (NH_3 and NMVOCs);
- soil cultivation and crop harvesting (PM).

2.1 Process description

2.1.1 Ammonia

NH_3 volatilisation occurs when NH_3 in solution is exposed to the atmosphere. The extent to which NH_3 is emitted depends on the chemical composition of the solution (including the concentration of NH_3), the temperature of the solution, the surface area exposed to the atmosphere and the resistance to NH_3 transport in the atmosphere.

Although most N fertilisers are applied as solids, there is usually sufficient moisture in the soil or air for the fertiliser to dissolve. High pH favours the volatilisation of NH_3 from many N fertilisers, hence the potential for volatilisation will tend to be larger on calcareous soils. Direct emissions of NH_3 only occur from fertilisers containing N as ammonium (NH_4^+) or if, as for urea, where the fertiliser is rapidly decomposed to NH_4^+. Those fertilisers only containing N as nitrate (NO_3^-) are not direct sources of NH_3 but may increase NH_3 emissions via crop foliage.

NH_3 emissions that occur in the 7 to 10 days after N fertiliser application include some emissions from the crop canopy, due to an increase in the concentration of N in the leaves of crops after the addition of fertiliser N. Emissions from the crop canopy that occur at this time cannot be distinguished from emissions that take place directly from applied N fertiliser and are included with N fertiliser emissions. Once direct NH_3 emissions after N fertiliser application have ceased, there may be a net emission of NH_3, or net deposition, depending on many factors, including the N status of the plant; the crop or plant growth stage; stresses such as drought and disease; the time of day; and the ambient NH_3 concentration. Later in the season, during grain filling and senescence, net NH_3 emissions from standing crops can again occur. The emission of NH_3 from standing crops is a complex process, as it is influenced by both the concentration of NH_3 in the air and environmental conditions. As a consequence, it has not yet been possible to develop a robust and usable methodology to calculate these emissions. NH_3 emissions may also be emitted from crop residues as they senesce and break down, since the degradation of proteins within the residues leads to the formation of NH_4^+.

NH_3 emissions occur when organic manures (livestock manure, sewage sludge and other organic wastes) are applied to land. As for N fertilisers, these emissions occur because a proportion of the N is present as NH_4^+ in the liquid fraction.

For further details see, Annex 1 (A1.1.1).

2.1.2 Nitric oxide

In agricultural soils, where pH is likely to be maintained above 5.0, nitrification is considered to be the dominant pathway of NO emission. Nitrification is the process by which microorganisms oxidise NH_4^+-N to NO_3^--N. The main determinants of NO production during crop production and in agricultural soils are mineral N concentration, temperature, soil carbon (C) concentration and soil moisture.

Increased nitrification is likely to occur after the application of fertilisers containing NH_4^+, soil cultivation and the incorporation of crop residues. Activities such as tillage and incorporation are considered to increase NO emissions by a factor of four, for periods of between 1 and 3 weeks.

The 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006) account for indirect N_2O emissions, i.e. those that result from the deposition of N emitted as NH_3 from N fertilisers, organic wastes, urine and dung N deposited on land grazed by livestock; N in crop residues (above and below ground), including N-fixing crops and forage/pasture renewal returned to soils; and N mineralisation associated with loss of soil organic matter resulting from change of land use or management on mineral soils. Since NO is produced as an intermediate product of nitrification and denitrification, indirect emissions should be accounted for here. For further details, see section 3.3.2 and Annex 2 (A2.2.1).

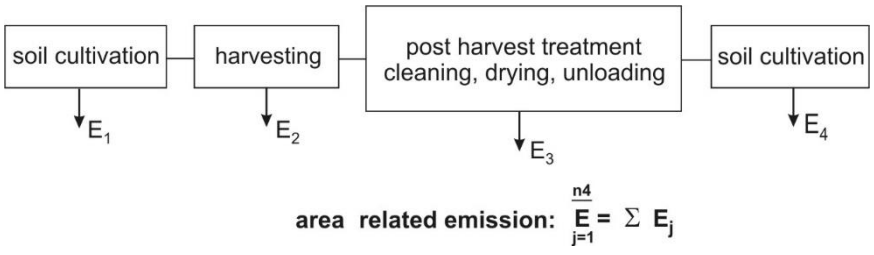
2.1.3 Non-methane volatile organic compounds

Emissions from crops may arise to attract pollinating insects, eliminate waste products or as a means of losing surplus energy. The NMVOCs emitted have proven difficult to quantify in atmospheric samples. Factors that can influence the emission of NMVOCs include temperature and light intensity, plant growth stage, water stress, air pollution and senescence. For further details see, Annex 3 (A3.1.1).

2.1.4 Particulate matter

The main sources of PM emissions from soil result from soil cultivation and crop harvesting, which together account for > 80 % of total PM_{10} emissions from tillage land (CEIP, 2015). These emissions originate at the sites at which the tractors and other machinery operate, and are thought to consist of a mixture of organic fragments from the crop and soil mineral and organic matter. There is considerable settling of dust close to the sources and washing out of fine particles by large particles. Field operations may also lead to the re-suspension of dust that has already settled (re-entrainment). Emissions of PM are dependent on climatic conditions, and in particular the moisture of the soil and crop surfaces.

Figure 2-1 Process scheme for PM emissions from crop production and agricultural soils



Emissions of PM vary according to the following:

- the type of crop;
- the physical properties of the particles;
- the origin of the particles, i.e. soil, plant or machinery;
- the meteorological conditions of the soil and/or produce before and during the operation (wind speed, temperature, rainfall, humidity);
- the type of operation;
- the parameters of the machinery (working speed, working capacity, working surface).

The processes which result in particulate emissions are largely low-temperature mechanical activities, and emissions are unlikely to include substantial quantities of condensable particulate material.
For further details, see Annex 4 (A4.1.1).

2.2 Measured emissions

2.2.1 Ammonia

Based on reported measurements and reviews of NH_3 from fertilisers, it was concluded that NH_3 emissions from urea are the most variable, ranging from 6 to 47 % of applied N, and are very dependent on factors such as soil type, weather conditions and application rates. In contrast, measured emissions from ammonium nitrate (AN) (and calcium AN (CAN)) are much smaller, never exceeding 4 % of applied N. There are fewer studies of other fertilisers such as ammonium sulphate (AS) and diammonium phosphate (DAP). Variations in emissions result from differences in soil type and time of application. In addition, application method (broadcast, incorporation and deep placement in the soil, etc.) will affect NH_3 emissions. The default emission factors (EFs) are based on broadcast application but incorporation or deep placement of fertiliser will need to be taken into account if it is practised.

There are relatively few studies on emissions from crops and crop residues. The emissions appear to be small (<1 – 3 kg ha^{-1} $year^{-1}$), but given the large areas dedicated to crop production, the emissions are likely to be significant at the national scale.

The field application of sewage sludge is a source of NH_3 emissions, but emissions are very uncertain.

For information related to livestock manure and organic wastes, see Chapters 3B and 5B.

Further information on measurement of NH_3 and EFs is provided in Annex 1 (A1.1.2).

2.2.2 Nitric oxide

A review of a global data set of NO measurements from 189 agricultural fields, but biased towards industrialised countries, has shown that NO emissions are closely related to the amount of N applied. Broadcasting fertiliser N results in greater NO emissions than incorporating fertiliser N or applying it as solution. Soils with organic C contents of > 3 % have significantly greater NO emissions than soils with < 3 % organic C, and good drainage, coarse texture and neutral pH promote NO emissions. Fertiliser and crop type do not appear to significantly influence NO emissions.

For further details, see Annex 2 (A2.2.2).

The proportion of N lost as NO from indirect emissions arising from N deposition to agricultural land is assumed to be the same as for the direct emissions. There are very few data on indirect emissions of NO from agricultural land.

2.2.3 Non-methane volatile organic compounds

Hewitt and Street (1992) concluded that only c. 700 plant species, mainly from North America, had been investigated as isoprene or monoterpene emitters. Few of these were agricultural crops, and quantitative data were available for only a few species. Many measurements had been made at temperatures higher than those prevailing in northern and western Europe. However, based on these limited data, a preliminary estimate of the order of magnitude of crop emissions can be made. Further information on how the methodology was developed is provided in Annex 3 (A3.1.1).

2.2.4 Particulate matter

Emissions from crop production arise from soil cultivation, harvesting and cleaning, of which soil cultivation is the largest source. In wet climates, the drying of crops gives rise to particularly large emissions, emitting more PM than any of the other activities. There are a wide range of different variables that have significant impacts on the emissions from the different activities. In general, the most important variable is the moisture of the soil and crop surface, but emissions will also very much depend on the crop type, soil type, cultivation method and weather conditions in general before and while working. Total dust emissions from crop management have a large mass fraction in the coarse fraction compared with other sources of PM or dust. This is typically the case for all sources of suspended or mechanically generated dust or PM, rather than combustion sources, and the latter has a much greater mass fraction in the fine and ultrafine PM fractions.

2.3 Controls

2.3.1 Ammonia

NH_3 emissions from the application of manure and fertiliser N can be reduced by implementing the United Nations Economic Commission for Europe (UNECE) Framework Advisory Code of Good Agricultural Practice for Reducing Ammonia Emissions https://www.unece.org/fileadmin/DAM/env/documents/2014/AIR/WGSR/eb.air.wg.5.2001.7.e.pdf.

Further guidance concerning measures to reduce NH_3 emissions from this source is available from *Options for Ammonia Abatement: Guidance from the UNECE Task Force on Reactive Nitrogen* https://www.clrtap-tfrn.org/content/options-ammonia-abatement-guidance-unece-task-force-reactive-nitrogen

and from Nitrogen Opportunities for Agriculture, Food & Environment. UNECE Guidance Document on Integrated Sustainable Nitrogen Management

https://unece.org/environment-policy/publications/guidance-document-integrated-sustainable-nitrogen-management

2.3.2 Nitric oxide

No potential controls have been proposed for NO emissions from fertilised crops, but the topic is discussed in Annex 2 (A2.2.3).

2.3.3 NMVOCs

No potential controls have been proposed for NMVOC emissions from fertilised crops.

2.3.4 Particulate matter (PM)

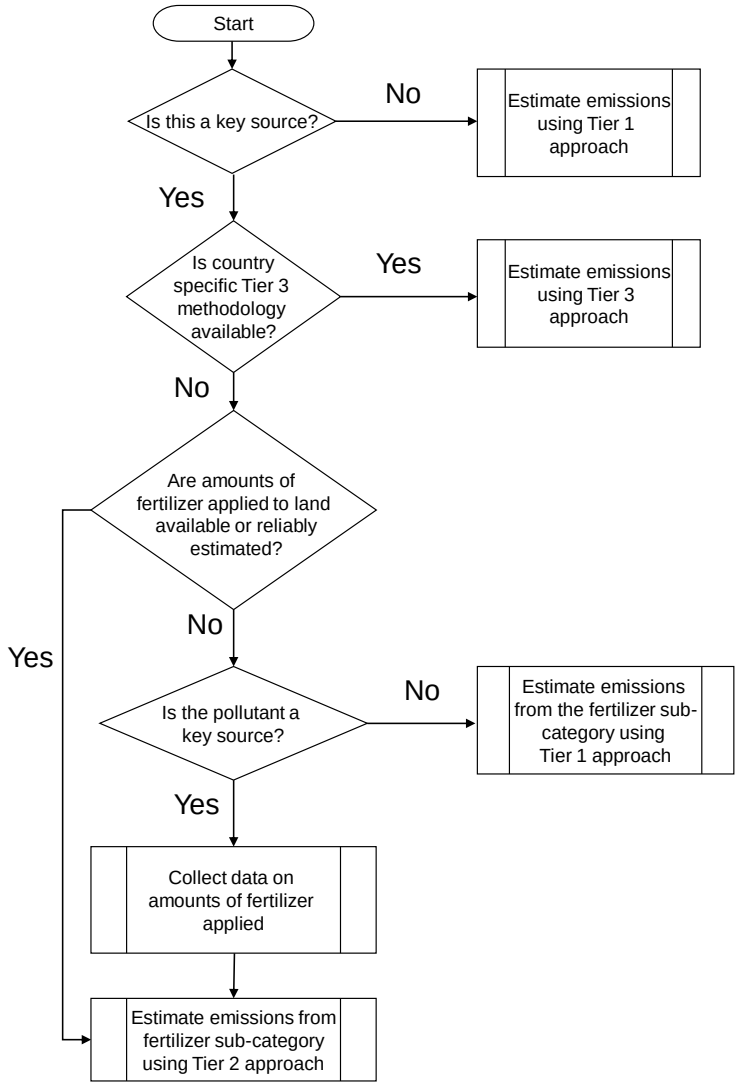
No potential controls have been proposed for PM emissions from tillage operations.

3 Methods

3.1 Choice of method

Error! Reference source not found. provides an example decision tree for this source category. Starting from the top left, it guides the user towards the most applicable approach. General guidance on the identification of key sources can be found in the general guidance chapters of the *EMEP/EEA air pollutant emission inventory guidebook*, namely Chapter 2, '*Key category analysis and methodological choice*' (EMEP/EEA, 2023).

Figure 3-1 Decision tree for source category 3.D Crop production and agricultural soils



3.2 Calculating emissions

Emissions of NH_3 resulting from the application, to land, of livestock manures, mineral N fertilisers, organic wastes and crop residues need to be reported under 3D. However, as indicated above, emissions of NH_3 from the application to land of livestock manures are calculated in Chapter 3B, while those relating to digestate from anaerobic digestion are calculated in Chapter 5B. This is because the emissions of NH_3 at one stage of manure management, e.g. during housing, influence the NH_3 emissions at later stages of manure management, e.g. during manure storage and application to land. Hence, the more NH_3 is emitted at early stages of manure management, the less N is available as a source of emission later. For this reason, emissions at the Tier 2 level are calculated sequentially using a mass-flow approach. The Tier 1 default EFs are derived from the Tier 2 mass-flow method.

Manure management also effects NH_3 emissions from grazed pastures. The more time grazing livestock are housed, the smaller the proportion of their excreta deposited on grazed pastures will be, and hence the smaller the emissions from those pastures.

Emissions from grazed pasture and after the application of livestock manures to land need to be reported separately. The guidance and both Tier 1 and Tier 2 methodologies for estimating emissions from livestock manures applied to land and from excreta deposited by livestock during grazing are presented in Chapter 3B.

There are currently no methodologies available for calculating the emissions from standing (living) crops.

Note that NO emissions are reported together with NO_2 emissions, as NO_x. The NO emissions are converted to NO_2 when reporting emissions of NO_x. Further information on NO is provided in Annex 2 (A2.1).

3.3 Default tier 1 approach

3.3.1 Algorithm

The Tier 1 approach for NH_3 and NO emissions from crop production and agricultural soils uses the general equation:

$$E_{pollutant} = AR_{N\_applied} \times EF_{pollutant} \quad (1)$$

where:

$E_{pollutant}$ = amount of pollutant emitted (kg a^{-1}),

$AR_{N\_applied}$ = amount of N applied in fertiliser, organic waste or crop residues (kg a^{-1}),

$EF_{pollutant}$ = EF of pollutant (kg kg^{-1}).

This equation is applied at the national level, equating $AR_{N\_applied}$ to the annual national total fertiliser N use, organic waste application or crop residues remaining on the soil surface.

The Tier 1 approach for NMVOC and PM emissions from crop production and agricultural soils uses the general equation:

$$E_{pollutant} = AR_{area} \times EF_{pollutant} \quad (2)$$

where $E_{pollutant}$ is the amount of pollutant emitted (in kg a^{-1}); AR_{area} is the area covered by crop (in ha); and $EF_{pollutant}$ is the EF of pollutant (in kg ha^{-1} a^{-1}).

The value of AR_{area} is equated to the utilised agricultural area (UAA), which includes all cropland, permanent pasture and rough grazing land.

3.3.2 Default emission factors

Table 3-1 Tier 1 EFs for source category 3.D

Tier 1 default EFs						
	Code	Name				
NFR Source Category	3.D	Inorganic N fertilisers, sewage sludge, other organic fertilisers, cultivated crops, crop residues and farm-level agricultural operations including storage, handling and transport of agricultural product				
Fuel	NA					
Not applicable						
Not estimated						
Pollutant	**Value**	**Unit**	**95 % confidence interval**		**Reference**	**NFR Code**
			Lower	**Upper**		
NH_3 from N fertiliser	0.085	kg NH_3 kg^{-1} fertiliser N applied	NC	NC	See Annex 1 1.2	3Da1
NH_3 from livestock manure applied or deposited to soil	See Tables 3.2 and 3.9 in Chapter 3B					3Da2a, 3Da3
NH_3 from sewage sludge	0.0066 or 0.13	kg NH_3 $capita^{-1}$ kg NH_3 (kg N applied) $^{-1}$	NC	NC	See Annex 1 (A1.1.2)	3Da2b
NH_3 emission from Other organic wastes	0.08	kg NH_3 (kg waste N applied)$^{-1}$	NC	NC	Method for fertiliser applications	3Da2c
NH_3 emission from crop residues	0.034	kg NH_3 kg^{-1} crop N residue N on soil surface for > 3 days	NC	NC	de Ruijter and Huismans (2019)	3Da4
NO from N applied in fertiliser, manure and excreta (a)	0.04	kg NO_2 kg^{-1} fertiliser and manure N applied	0.005	0.104	Skiba et al (2021)	3Da1 (fertiliser), 3Da2a (manure), 3Da3 (excreta)
NO from sewage sludge (a)	0.002	kg NO_2 $capita^{-1}$	NC	NC	See Annex 2 (A2.3)	3Da2b
NO emission from other organic wastes (a)	0.04	kg NO_2 kg^{-1} waste N applied	0.005	0.104	Skiba et al (2021)	3Da2c
NMVOC from standing crops	0.86	kg ha^{-1}	0.22	3.44	König et al. (1995), Lamb et al. (1993)	3De
PM_{10} from agricultural operations	1.56	kg ha^{-1}	0.78	7.8	van der Hoek and Hinz (2007)	3Dc
$PM_{2.5}$ from agricultural operations	0.06	kg ha^{-1}	0.03	0.3	van der Hoek and Hinz (2007)	3Dc
TSP	1.56	kg ha^{-1}	0.78	7.8	van der Hoek and Hinz (2007)	3Dc

(a) NO emissions are reported as NO_2. NC, not calculable.

Ammonia

The Tier 1 default NH_3 EF for emissions from fertiliser has been derived as a mean of default EFs for individual N fertilisers weighted according to their use as reported by the International Fertilizer Association (IFA) for Europe in 2019 (https://www.ifastat.org/) and by the distribution of agricultural

land between normal and high pH (>7.0). More information on the key equations and assumptions behind these defaults can be found in Annex 1.

Emissions from livestock manure applied to land or deposited during grazing should be calculated using the method described in section 3.3 of Chapter 3B.

The emission from sewage sludge (3Da2b) is calculated by multiplying the emission per capita in Table 3-1 by the human population of the relevant territory. The contribution of digestates produced as a result of anaerobic digestion of organic wastes (including manure) to the NH_3 emission from N applied in other organic wastes (3Da2c) should be obtained from Chapter 5B2 (Biological treatment of waste — Anaerobic digestion at biogas facilities).

The emission from crop residues is calculated from the amount of N in crop residues on the soil surface from which NH_3 may be emitted, and an EF. The derivation of the Tier 1 EF is given in Annex 1.

Nitric oxide

The NO EF follows the recommendation of Skiba et al (2021) that there was no justification for changing the value from that calculated from Table 6 of Stehfest and Bouwman (2006), as the weighted average of the EFs for cropland and grassland.

Emissions from livestock manure applied to land (3Da2a) should be calculated by multiplying the annual average population of each livestock category by the appropriate Nex values in Table 3-7 of Chapter 3B. The Tier 1 methodology does not distinguish between emissions from manure applied to land (3Da2a) or those from excreta deposited during grazing (3Da3). For each livestock category, the emissions should be reported under 3Da2a if the livestock are in animal housing for most of the year or under 3Da3 if they are predominantly grazed.

The emission from sewage sludge (3Da2b) is calculated by multiplying the emission per capita in Table 3.1 by the human population of the relevant territory.

The contribution of digestates produced as a result of anaerobic digestion of organic wastes (including manure) to the N applied in other organic wastes (3Da2c) should be obtained from Chapter 5B2 (Biological treatment of waste — Anaerobic digestion at biogas facilities).

Non-methane volatile organic compounds

A Tier 1 EF for NMVOCs is presented in Table 3-1. This has been determined by aggregating detailed data provided by König et al. (1995) and Lamb et al. (1993). A number of assumptions have to be incorporated into the aggregation methodology.

The underlying data and method for determining the Tier 1 EF are presented and explained under the description of the Tier 2 methodology (section 3.4).

Particulate matter

The Tier 1 EFs for PM do not include emissions from fertiliser, pesticides or from grassland, e.g. hay making. These emissions are mainly from combine harvesting and soil cultivation. Detailed information on PM emissions from agricultural fields is included in Annex 4. The Tier 1 EFs are based on the work of van der Hoek and Hinz (2007), but represent a simplification and aggregation of the detailed data, to give a single value for PM emissions per hectare.

3.3.3 Activity data

The UAA for most European countries can be obtained from Eurostat. Information is required on the annual national consumption of total N fertiliser. Annual fertiliser consumption data may be collected from official country statistics, often recorded as fertiliser sales and/or as domestic production and imports. The amounts and types of sewage sludge applied to land will also need to be known. To calculate emissions of NO, data on additions of N in manures and excreta are also needed. Methods to estimate emissions of NO after manure application and from excreta deposited during grazing are provided in Chapter 3.B, Manure management.

3.4 Tier 2, technology-specific approach and emission factors

3.4.1 Algorithm

Ammonia

Ammonia emissions from soils

NH_3 emissions from fertilisers and emissions from foliage in the weeks immediately after fertiliser application are treated here as a single integrated term because it is not possible to separately identify the two sources experimentally. These are estimated as proportional losses of the fertiliser N use for each of the main fertiliser categories. Emissions from unfertilised crops are considered to be zero.

The methodology was developed from the results of a meta-analysis of trials in which NH_3 emissions were measured following the application of 31 different types of N fertiliser. Details of the meta-analysis and development of the methodology to estimate Tier 2 emissions are provided in Annex 1 (A1.1.2).

3.D.a.1 emissions after N fertiliser application are calculated as outlined below.

Step 1

Quantify the areas in which the soil pH is above or below 7.0. For the purpose of calculating emissions after N fertiliser application, the area with soils of < pH 7.0 will be designated as 'normal' pH region, while the area with soils of > pH 7.0 will be designated as the 'high' pH region.

Step 2

Quantify the amounts of each fertiliser type shown in Table 3.2 that are applied to agricultural and horticultural land.

Step 3

Quantify the amounts of each fertiliser type applied in each of the two regions. If these data are not available or cannot be estimated by agricultural experts, estimate this amount as follows:

$$m_{fert\_i,j} = m_{fert\_i} * area_j / \sum_{j=1}^{2} area_j \qquad (3)$$

where $m_{fert\_i,j}$ is the mass (in kg) of fertiliser type *i* in pH region *j*, m_{fert_i} is the mass of fertiliser type *i* consumed nationally (kg a^{-1}, N) and $area_j$ is the area of pH region *j* (in ha) in the country.

Step 4

Calculate the emission using the following equation:

$$E_{fert\_NH3} = \sum_{i=1}^{I} \sum_{j=1}^{2} (m_{fert\_i,j} \cdot EF_{i,j}) \quad (4)$$

where E_{fert_NH3} is the emission (in kg a^{-1} NH_3); and $EF_{i,j}$ is the EF for fertiliser type *i* in pH region *j* (in kg NH_3 (kg N applied) $^{-1}$).

Table 3-2 EFs for NH_3 emissions from fertilisers (in g NH_3 (kg N applied)$^{-1}$)

	normal pH ([a])	high pH ([b])
Anhydrous ammonia (AH)	20	20
AN	24	52
Ammonium phosphate (AP) ([c])	84	187
AS	84	187
CAN	24	52
NK mixtures ([d])	24	52
NPK mixtures ([d])	84	187
NP mixtures ([d])	84	187
N solutions ([e])	87	161
Other straight N compounds ([f])	24	187
Urea[(g)]	195	206

([a]) A 'normal' pH is a pH of 7.0 or below.
([b]) A 'high' pH is a pH of more than 7.0 (usually calcareous soils).
([c]) AP is the sum of ammonium monophosphate (MAP) and diammonium phosphate (DAP).
([d]) NK mixtures are equivalent to AN, NPK and NP mixtures, which are 50 % MAP plus 50 % DAP.
([e]) N solutions are equivalent to urea AN.
([f]) Other straight N compounds and equivalent to calcium nitrate.
(g) Urea is an organic compound with the chemical formula $CO(NH_2)_2$.

For **3.D.a.2.b**, Emission from sewage sludge applied to soil (E_{sludge_NH3}; kg a^{-1} NH_3), no Tier 2 method is proposed. The Tier 1 estimate should be used.

For **3.D.a.2.c**, Emission from other organic fertilisers (E_{Other_NH3}; kg a^{-1} NH_3), Tier 1 methodology should be used. For the emission of NH_3 from N applied in digestates derived from material other than manure, values should be obtained from Chapter 5B2 (Biological treatment of waste — Anaerobic digestion at biogas facilities), See Chapter 3.B. for emissions **3.D.a.2.a** (Animal manure applied to soils) and **3.D.a.3** (Urine and dung deposited by grazing animals).

Ammonia emissions from crop residues

3.D.a.4 emissions from crop residues are calculated as outlined below.

This methodology applies to direct emissions from crop residues on the field. It also applies to situations where N is applied as synthetic fertiliser or manure to crop residues present on the soil surface at the time of application. In these situations, NH_3 emissions are considered to take place from both the crop residues and from the N fertilizer or manure. independently from one another. Any smothering effect of manure is likely to be small. Hence, while inventory compilers do not need to take account of these other emissions when calculating emissions from residues a separate calculation of emissions from fertilizer of manure is needed, and will be calculated according to the methods given in section 3.D.a.1. This is in contrast to emissions from living crop tissue, since these are assumed to be incorporated into the emissions from fertiliser and manure.

Crop residues are defined as those parts of the crop left on the soil surface following harvest or after another management action such as cutting grass for silage or hay, or trimming pasture to stimulate fresh growth. Volunteer crops killed by the use of herbicides, potato haulms dessicated by acid application and green manures that die after frost are also to be included in the calculation. Ammonia emissions from crop residues are related to the amount and N content of the residue left on the soil surface. Information on farm practices (degree of incorporation of residues, the application of herbicides or dessicants and mowing frequency of grass), harvested crop areas, and the amounts and N contents of the residues are needed to calculate emissions from crop residues at national scale. Further details are provided in Annex 1 based on the work of de Ruijter and Huijsmans (2019).

Calculation of NH_3 from crop residues left in field

The NH_3 emission is calculated from the amount of N in crop residues on the soil surface from which NH_3 may be emitted, and an EF. The equation makes allowance for the fraction of crop residues that are burned and will not therefore contribute to NH_3 emissions.

$$NH_{3\_cropresidues} = (17/14) * \Sigma (A_T * N\_Load_T * F_T) * EF_{\_cropresidues(T)}$$

where $NH_{3\_cropresidues}$ is the emission of NH_3 to be reported (kg),
A_T is the area of the *T* th crop (ha),
N_Load_T is the above-ground production of crop residues from the *T* th crop (kg N ha^{-1} yr^{-1}),
F_T is the fraction of the crop residues from the *T* th crop that produce NH_3 emissions, i.e. the fraction that remains on the soil surface for longer than 3 days after harvesting
$EF_{\_cropresidues(T)}$ is the EF (kg NH_3-N (kg N_load)$^{-1}$) for crop *T*.
The factor (17/14) converts NH_3-N to NH_3.

The N in crop residues considered here to contribute to NH_3 emission are those that remain on the soil surface for more than 3 days in each year. Farming operations that remove crop residues from the soil surface include harvesting, incorporation and burning. The crop residue N also includes the N those created during forage or pasture renewal and green manures.

N_Load_T can be calculated by adapting the part of Equation 11.6 of IPCC (2019) that estimates above-ground residues, since only those are considered to emit NH_3:

$$N\_Load_T = AG_{DM(T)} * N_{AG(T)}$$

Where
$AG_{DM(T)}$ = annual total amount of above-ground crop residue for crop *T*, kg DM $ha^{-1}yr^{-1}$.

$N_{AG(T)}$ = N content of above-ground residues for crop *T*, kg N (kg DM)$^{-1}$. Default values from IPCC (2019) Table 11.1a are shown in Table 3.3 below.

IPPC (2019) provides two methods of calculating $AG_{DM(T)}$. The first uses the following equation:

$$AG_{DM(T)} = Yield\ Fresh_{(T)} * DRY * R_{AG(T)}$$

where

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

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

$R_{(AG\,(T)}$ is the ratio of above-ground residue dry matter to harvested yield

Values of $R_{AG(T)}$ from IPCC (2019) Table 11.1a are shown in Table 3.3 below.

Alternatively, $AG_{DM_{(T)}}$ may be estimated using the method and data in IPCC (2019; Table 11.2)

Because different crop types vary in residue:yield ratios, renewal time and N contents, separate calculations should be performed for major crop types. At a minimum, crops should 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., potatoes, sugarbeet);
4) N-fixing forage crops (alfalfa, clover);
5) other forages including perennial grasses and grass/clover pastures.

The $EF_{\_cropresidues}$ is derived from the model of de Ruijter and Huijsmans (2019) and depends on the N concentration in crop residues ($N_{AG(T)}$; kg N (kg DM)$^{-1}$):

If the $N_{AG(T)} \leq 0.0132$ kg N (kg DM)$^{-1}$

$EF_{\_cropresidues} = 0$

Otherwise

$EF_{\_cropresidues} = (410 * N_{AG(T)} - 5.42)/100$

Default data to calculate $EF_{\_cropresidues}$ are provided in Table 3-3.

Table 3-3 The Ratio of above- ground residue dry matter to harvested yield, Dry matter fraction of harvested product and N content (kg kg^{-1} dry matter) in residues (kg ha^{-1}) taken from Table 11A of IPCC (2019). Note that some crops (greyed out) have default N contents that would lead to EF values of zero.

Crops	N content of above-ground residues (*N AG(T)*) (kg N (kg DM)$^{-1}$)	Ratio of above- ground residue dry matter to harvested yield *(RAG (T))*	Dry matter fraction of harvested product (*DRY*)
Generic value for crops not indicated below	0.008	1.0	0.85
Generic Grains	0.006	1.3	0.88
Winter Wheat	0.006	1.3	0.89
Spring Wheat	0.006	1.3	0.89
Barley	0.007	1.2	0.89
Oats	0.007	1.3	0.89
Maize	0.006	1.0	0.87
Rye	0.005	1.6	0.88
Rice	0.007	1.4	0.89
Millet	0.007	1.4	0.90
Sorghum	0.007	1.4	0.89
Beans and Pulses	0.008	2.1	0.91
Soybeans	0.008	2.1	0.91
Potatoes and Tubers	0.019	0.4	0.22
Peanuts	0.016	1.0	0.94
Alfalfa	0.027	0.3	0.90
Non-legume hay	0.015	0.3	0.90
N-fixing forages	0.027	0.3	0.90
Non-N-fixing forages	0.015	0.3	0.90
Perennial Grasses	0.015	0.3	0.90
Grass-Clover Mixtures	0.025	0.3	0.90

Not all these crops will be grown in all Parties and for some of the specialist crops national data may not record the areas or yields. Hence Parties are not expected to provide an emission estimate for all the crops listed.

The value of F_T can be calculated by the following equation, adapted from IPCC (2019) Equation 11.6:

$$F_T = 1 - (Frac_{Incorp(T)} + Frac_{Remove(T)} + Frac_{Burn(T)} * C_f)$$

$Frac_{Incorp(T)}$ = fraction of residues from crop T incorporated **within 3 days of harvesting**, dimensionless,
$Frac_{Remove(T)}$ = fraction of residues from crop T removed **within 3 days of harvesting**, dimensionless,
$Frac_{Burnt(T)}$ = fraction of annual harvested area of crop T burnt **within 3 days of harvesting**, dimensionless,
C_f = combustion factor (dimensionless) (refer to IPCC (2019) Chapter 2, Table 2.6).

More information on the method of De Ruijter and Huijsmans (2019) is given in Annex 1 should any Party consider their more detailed crop data may give a more robust estimate of NH_3 emissions from crop residues.

Nitric oxide

There is no Tier 2 methodology for NO. Tier 1 methodology should be used.

If the Tier 2 methodology has been used to calculate NH_3 emissions resulting from manure management (Chapter 3B, section 3.3.1):

1. when calculating emissions attributed to 3Da2a, the N applied should be calculated as the sum of $m_{applic\_slurry\_N}$ and $m_{applic\_solid\_N}$ (Step 11);
2. when calculating emissions attributed to 3Da3, the N applied should be equated to m_{graz_N} (Step 3).

Otherwise, see the Tier 1 methodology of the current chapter.

Non-methane volatile organic compounds

The method for determining Tier 2 EFs is presented below. The same method is used to generate the Tier 1 EF presented in Table 3-4, but a number of assumptions and the use of additional data are required. These are also provided in the information that follows so that the methodology can be used with default values and assumptions if country-specific data (yield, dry matter content, crop areas by crop type) are not available.

The EFs for NMVOC emissions are based on the results of König et al. (1995) and Lamb et al. (1993). Because of the significant differences in emissions from wheat and rye, an average of the NMVOC EFs estimated by König et al. (1995) and Lamb et al. (1993) was chosen for use. The NMVOC EFs for rape and grassland are estimated based on König et al. (1995).

The yield and crop-type allocation is based on data from the Food and Agriculture Organization of the United Nations (FAO's) agricultural statistics. For more information, see Annex 3.

Table 3-4 Estimation of NMVOC Tier1 EFs in kg ha^{-1} a^{-1}

	NMVOC, kg DM^{-1} ha^{-1}*	Fraction of year emitting	NMVOC, kg DM^{-1} a^{-1}	Mean yield of crop, kg DM ha^{-1}	NMVOC, kg $ha^{-1}a^{-1}$	Crops distribution	Weighted EF, kg NMVOC ha^{-1} a^{-1}
Wheat	2.60×10^{-8}	0.3	6.82×10^{-5}	4700	0.32	0.35	0.11
Rye	1.41×10^{-7}	0.3	3.70×10^{-4}	2800	1.03	0.05	0.05
Rape	2.02×10^{-7}	0.3	5.30×10^{-4}	2500	1.34	0.10	0.13
Grass (15 °C)	1.03×10^{-8}	0.5	4.51×10^{-5}	9000	0.41	0.25	0.10
Grass (25 °C)	4.67×10^{-8}	0.5	2.05×10^{-4}	9000	1.85	0.25	0.46
Tier1 NMVOC EF (sum of weighted EFs)							0.86

*DM: dry matter; Source: König et al. (1995), Lamb et al. (1993), FAO (2012).

The data provided in Table 3-5 are used to arrive at these values, and allow the use of country-specific data if they are available in order to determine more accurate EFs.

Table 3-5 NMVOC emissions from agricultural crops, in kg NMVOC kg^{-1} ha^{-1}

Crop	Isoprene	Terpenes	Alcohols	Aldehydes	Ketones	Ethers and others	Total NMVOC emission, kg NMVOC kg DM^{-1} ha^{-1}
			kg NMVOC kg DM^{-1} ha^{-1}				
Wheat ([a])	–	–	8.00×10^{-10}	2.80×10^{-9}	2.20×10^{-9}	5.10×10^{-9}	1.09×10^{-8}
Wheat ([b])	2.05×10^{-8}	8.20×10^{-9}	–	–	–	1.23×10^{-8}	4.10×10^{-8}
Rye ([a])	–	7.74×10^{-8}	1.69×10^{-7}	1.92×10^{-8}	–	–	2.66×10^{-7}
Rye ([b])	3.20×10^{-9}	8.00×10^{-9}	–	–	–	4.80×10^{-9}	1.60×10^{-8}
Rape ([a])	–	7.46×10^{-8}	5.20×10^{-8}	1.10×10^{-8}	–	6.40×10^{-8}	2.02×10^{-7}
Grass (15 °C) ([a])	2.00×10^{-10}	6.20×10^{-9}	8.00×10^{-10}	1.30×10^{-9}	–	1.80×10^{-9}	1.03×10^{-8}
Grass (25 °C) ([a])	1.00×10^{-9}	8.70×10^{-9}	1.00×10^{-8}	5.90×10^{-9}	6.20×10^{-9}	1.49×10^{-8}	4.67×10^{-8}

([a]) König et al. (1995).
([b]) Lamb et al. (1993).

Particulate matter

PM emissions should be calculated by multiplying the cultivated area of each crop by an EF and by the number of times the emitting practice is carried out.

$$E_{PM} = \sum_{t=1}^{T} \sum_{n=0}^{N_{t,k}} EF_{PM\_t,k} \cdot A_t \cdot n \qquad (5)$$

where E_{PM} is the emission of PM_{10} or $PM_{2.5}$ from the t_{th} crop in kg a^{-1}; T is the number of crops grown; A_t is the annual cropped area of the t_{th} crop in ha; $N_{t,k}$ is the number of times the k_{th} operation is performed on the t_{th} crop, in a^{-1}; and $EF_{PM\_t,k}$ is the EF for the k_{th} operation of the t^{th} crop, in kg ha^{-1}.

The default values of the EF are shown in **Error! Reference source not found.** to Table 3-9. However, country-specific information is needed on the number of times that each operation is performed for each crop type during the course of a year. Care should also be taken to account for crop areas that provide more than one harvest per year.

It is important to note that the PM emissions calculated here are intended to reflect the amounts found immediately adjacent to the field operations. A substantial proportion of this emission will normally be deposited within a short distance of the location at which it is generated.

The following tables present Tier 2 PM_{10} and $PM_{2.5}$ EFs for the different agricultural crop operations (Source: Van der Hoek and Hinz, 2007). EFs for dry climate conditions (Mediterranean climate) and wet climate conditions (all other climates) are presented in separate tables. The PM_{10} and $PM_{2.5}$ EFs represent filterable PM emissions.

Table 3-6 Tier 2 EFs for agricultural crop operations, in kg ha^{-1} PM_{10}, wet climate conditions

Crop		Soil cultivation	Harvesting	Cleaning	Drying
	I	1	2	3	4
Wheat	1	0.25	2.7	0.19	0.56
Rye	2	0.25	2.0	0.16	0.37
Barley	3	0.25	2.3	0.16	0.43
Oats	4	0.25	3.4	0.25	0.66
Other arable	5	0.25	NC	NC	NC
Grass	6	0.25	0.25	0	0

Note: grass includes hay making only.

Table 3-7 Tier 2 EFs for agricultural crop operations, in kg ha–1 PM10, dry climate conditions

Crop		Soil cultivation	Harvesting	Cleaning	Drying
	I	1	2	3	4
Wheat	1	2.25	2.45	0.19	0
Rye	2	2.25	1.85	0.16	0
Barley	3	2.25	2.05	0.16	0
Oat	4	2.25	3.10	0.25	0
Other arable	5	2.25	NC	NC	NC
Grass	6	2.25	1.25	0	0

Note: grass includes hay making only.

Table 3-8 Tier 2 EFs for agricultural crop operations, in kg ha–1 PM2.5, wet climate conditions

Crop		Soil cultivation	Harvesting	Cleaning	Drying
	I	1	2	3	4
Wheat	1	0.015	0.02	0.009	0.168
Rye	2	0.015	0.015	0.008	0.111
Barley	3	0.015	0.016	0.008	0.129
Oat	4	0.015	0.025	0.0125	0.198
Other arable	5	0.015	NC	NC	NC
Grass	6	0.015	0.01	0	0

Note: grass includes hay making only.

Table 3-9 Tier 2 EFs for agricultural crop operations, in kg ha–1 PM2.5, dry climate conditions

Crop		Soil cultivation	Harvesting	Cleaning	Drying
	I	1	2	3	4
Wheat	1	0.12	0.098	0.0095	0
Rye	2	0.12	0.074	0.008	0
Barley	3	0.12	0.082	0.008	0
Oat	4	0.12	0.125	0.0125	0
Other arable	5	0.12	NC	NC	NC
Grass	6	0.12	0.05	0	0

Note: grass includes haymaking only.

3.4.2 Activity data

Information is required on the annual national consumption of the N fertiliser types shown in Annex 1, Table A1.1. Annual fertiliser consumption data may be collected from official country statistics, often recorded as fertiliser sales and/or as domestic production and imports. Fertiliser use also needs to be disaggregated by fertiliser type. In addition, if AS or DAP are significant sources, then information will be needed on the amounts of those fertilisers applied. 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.

If spatially disaggregated inventories of fertilised culture emissions are required (see section 4.7 below), information on the spatial distribution of different crop types and average N fertiliser inputs to each crop type may be used. In the absence of data on the use of different fertilisers for crop types, the average N fertiliser inputs to crops may be combined with the average NH_3 EF for a country: estimated total NH_3 emission/total N fertiliser consumption.

The sources of activity data needed for calculating emissions from livestock manures are provided in Chapter 3B.

For 'Other organic wastes', guidance related to activity data is available for digestates from anaerobic digestion in Chapter 5B2 and for domestic compost in Chapter 5B1.

For crop residues the following information is needed on the crop area harvested, A (ha). These data, by crop, should be available from national statistics. Where two crops are grown in a single year, including green manures, calculation should be made for both crops. Only areas of outdoor crops are to be included. Data on crop yield statistics (yields and area harvested, by crop) may be obtained from national sources. If such data are not available, FAO publishes data on crop production: (http://fao.org/faostat/). Since yield statistics for many crops are reported as field-dry or fresh weight, a correction factor should be applied to estimate dry matter yields (Crop(T)) where appropriate (Equation 11.7). The proper correction to be used is dependent on the standards that are applied for yield reporting, which may vary between countries. Alternatively, the default values for dry matter content given in IPCC (2019) Table 11.1a may be used.

3.5 Tier 3 emission modelling and use of facility data

3.5.1 Algorithm

Tier 3 methodologies are those that result in more accurate estimates of emissions than would be achieved using the Tier 2 methodology. This could include the use of alternative EFs, based on local measurement, the use of more detailed activity data and EFs, or the use of process-based models. Users are encouraged to use Tier 3 methodologies whenever possible. If measures are taken to reduce emissions, such as those mentioned in section 2.3 above, it may be necessary to use a Tier 3 methodology to gain acceptance of the effect on emissions. For example, immediate incorporation of mineral fertiliser would reduce direct emissions, so the EF for the relevant type of fertiliser would require modification. In contrast, reducing N fertiliser use by balancing fertiliser applications to crop requirements would not require a Tier 3 approach, since the effect would be adequately reflected by the change in the activity data.

For estimating NH_3 emissions using Tier 3 methodology, process-based models are useful because, in appropriate forms, they can relate the soil and environmental variables responsible for NH_3 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 be used only after validation by representative experimental measurements.

An example of a simple process-based model for estimating NH_3 emissions from fertiliser applications to agricultural land is provided by Misselbrook et al. (2004). This has been incorporated into the United Kingdom's National Ammonia Reduction Strategy Evaluation System (NARSES) model and used for the construction of the United Kingdom NH_3 emission inventory. Important influencing variables which are included in this model are the type of N fertiliser, soil pH, land use type, application rate, rainfall and temperature. Each fertiliser type is associated with a maximum potential emission (EF_{max}), which is modified by functions relating to the other variables (soil pH, land use, etc.) to give an EF for a given scenario:

$$EF = EF_{max} \times RF_{soilpH} \times RF_{landuse} \times RF_{rate} \times RF_{rainfall} \times RF_{temperature} \quad (6)$$

where RF is the reduction factor, expressed as a proportion, associated with the variable.

3.5.2 Activity data

Data on the type of N fertiliser applied, soil pH, land use, application rate, rainfall and temperature will typically be required. Activity data for model input can be gathered from country-specific databases, trade associations (preferred) or, if these data are unavailable, can be found in different international databases: the International Fertilizer Association (https://www.ifastat.org/databases/plant-nutrition), the International Food Policy Research Institute (IFPRI) database; the International Soil Reference and Information Centre (ISRIC) in Wageningen, the Netherlands (www.isric.org); Eurostat (http://ec.europa.eu/eurostat/); or the CAPRI database (http://www.capri-model.org/).

4 Data quality

4.1 Completeness

All nitrogenous fertilisers and all cropped land should be included. Emissions occurring after the application of manure, calculated in Chapter 3B, also need to be included, together with emissions that occur during grazing and after the application of sewage sludge**.**

4.2 Avoiding double counting with other sectors

Caution is required to account for the possible double counting of fertiliser/foliar emissions from grazed grassland. If only the distribution of total grassland is available, estimates would need to be made of the fraction that is grazed, while account of the temporal overlap of grazing and emissions from the application of N fertilisers and livestock manure should also be taken.

4.3 Verification

There are no direct methods to evaluate total inventory estimates of NH_3 emissions from croplands, and verification is dependent on laboratory and micrometeorological field studies of emissions from example situations. In particular, many studies have focused on laboratory measurements and there

is a need to provide long-term field measurements using micrometeorological techniques to estimate NH_3 fluxes over a range of crop types in different climates.

Emissions of NO, NMVOC and PM cannot be verified except by field studies of emissions from example situations.

4.4 Developing a consistent time series and recalculation

General guidance on developing a consistent time series is given in Chapter 4 of the *EMEP/EEA air pollutant emission inventory guidebook*, 'Time series consistency' (EMEP/EEA, 2023).

Ideally, the same method is used throughout the entire time series. However, the detail and disaggregation of emissions estimates from this source category may improve over time. In cases for which some historic data are missing, it may be necessary to derive the data using other references or data sets. Inter-annual changes in EFs are not expected unless mitigation measures are undertaken. These factors should be changed with only proper justification and documentation. If updated defaults for any of these variables become available through future research, inventory agencies must recalculate their historical emissions. It is important that the methods used reflect the results of action taken to reduce emissions, and that the methods and results are thoroughly documented. If policy measures are implemented such that activity data are affected directly (e.g. increased efficiency of fertiliser use resulting in a decrease in fertiliser consumption), the effect of the policy measures on emissions will be transparent, assuming the activity data are carefully documented. In cases in which policy measures have an indirect effect on activity data or EFs (e.g. a change to the timing of fertiliser N application), inventory input data should reflect these effects. The inventory text should thoroughly explain the effect of the policies on the input data.

4.5 Uncertainty assessment

General guidance on quantifying uncertainties in emission estimates is given in Chapter 5 of the Guidebook, 'Uncertainties' (EMEP/EEA, 2023). In the following sections, the results of some previous studies of uncertainties in emission estimates from agricultural sources are discussed.

4.5.1 Ammonia

The main uncertainty lies in the generalisation of EFs, rather than the areas of crops under cultivation, which are probably accurate in most countries to ±5 %. The standard deviation in the NH_3 measurements from mineral fertiliser are at the same level as the average measured emission in per cent. The accuracies of overall emissions estimates are probably no better than ±50 %.

4.5.2 Nitric oxide

The relative 95 % confidence interval for the NO emission estimates may be regarded as from -80 % to +406 %, as given by Stehfest and Bouwman (2006); thus, the overall uncertainty is considered to be a factor of five (see also Annex 3, A3.3.2).

4.5.3 Non-methane volatile organic compounds

For NMVOCs, the uncertainty in the emission potential of plant species accounts for about half of the overall uncertainty of a factor of four for, e.g. an annual emission inventory of Great Britain (Stewart et al., 2003). See also Annex 3.

4.5.4 Particulate matter

No uncertainty can be given for the first estimates of PM, but uncertainty will be probably in the range of one order of magnitude depending on the variations in EFs and activity data.

4.5.5 Activity data uncertainties

Application of fertiliser N may be estimated with an accuracy of ±10 %; other factors, such as returns of N in manures, may be estimated to within ±25 %. With respect to national data on crop areas, an uncertainty of < 5 % is assumed, with a normal distribution.

4.6 Inventory quality assurance/quality control (QA/QC)

Guidance on the checks of the emission estimates that should be undertaken by the persons preparing the inventory are given in the Chapter 6 of the general guidance chapters, 'Inventory management, improvement and QA/QC' (EMEP/EEA, 2023).

4.7 Gridding

Emissions due to N fertiliser application may be spatially, as well as temporally, disaggregated using census data on the distribution of different crops and the application data statistics, together with mean fertiliser N inputs to those crops, as outlined in Annex 1 (A1.1.2.)

NMVOC emissions from some major agricultural crops (Table 3-4) enable some spatial disaggregation of agricultural NMVOC emissions. Emissions of NMVOCs are also likely to differ according to crop growth stage, soil type, cultivation and weather conditions. Some temporal disaggregation may be possible if seasonal variations in emissions by non-agricultural plants can be assumed to be valid for fertilised crops.

The specific yield is one factor that may influence PM emissions during harvesting. More important are climatic conditions and soil composition in the particular cereal-growing regions. These are important because there are large regional differences in plant production depending on the soil and climatic properties and the requirements of the end user.

4.8 Reporting and documentation

General guidance on reporting and documentation is given in the general guidance chapter 'Inventory management, improvement and QA/QC' (Chapter 6) of the Guidebook.

The main supplementary documentation required for applying the estimates in this chapter are details of national N fertiliser consumption and the areas of major crops. The approximate timing of soil cultivation, including crop residue incorporation, will also be useful. If disaggregated estimates are to be made, details on N application rates to crops and spatially disaggregated crop distribution are needed.

The use of temperature and soil pH-dependent data presupposes knowledge and documentation of regional spring air temperatures and soil pH distribution.

5 Glossary

AN	Ammonium nitrate

AP	Ammonium phosphate
AS	Ammonium sulphate
CAN	Calcium ammonium nitrate
CEC	Cation exchange capacity
DAP	Di-ammonium phosphate
EF	Emission factor
FAO	Food and Agriculture Organization of the United Nations
IFA	International Fertilizer Industry Association
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
NMHC	Non-methane hydrocarbon
OVOC	Oxidised volatile organic compound
RAINS	Regional Air Pollution and Simulation
REML	Residual maximum likelihood
UAA	Utilised agricultural area

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7 Point of enquiry

Enquiries concerning this chapter should be directed to the relevant leader(s) of the Task Force on Emission Inventories and Projections' (TFEIP's) Expert Panel on Agriculture and Nature. Please refer to the TFEIP website (tfeip-secretariat.org/) for the contact details of the current expert panel leaders.

Annex 1 Ammonia

Supplementary information is given in the annexes.

A1.1 Description of sources

A1.1.1 Process description

NH_3 volatilisation is a physico-chemical process which results from the equilibrium (described by Henry's law) between gaseous phase (g) NH_3 and NH_3 in solution (aq) (Equation A1.1). NH_3 in solution is in turn maintained by the equilibrium between NH_4^+ and NH_3 (Equation A1.2):

$$NH_3\ (aq) \leftrightarrow NH_3\ (g) \qquad (A1.1)$$

$$NH_4^+\ (aq) \leftrightarrow NH_3\ (aq) + H^+\ (aq) \qquad (A1.2)$$

High pH (i.e. a low concentration of hydrogen ions (H^+) in solution) favours the right-hand side of Equation A1.2, resulting in a greater concentration of NH_3 in solution and also, therefore, in the gaseous phase. Thus, if the soil is buffered at values of less than c. pH 7, the dominant form of ammoniacal-N (NH_x) will be NH_4^+ and the potential for volatilisation will be small. In contrast, if the soil is buffered at higher pH values, the dominant form of NH_x will be NH_3 and the potential for volatilisation will be large, although other chemical equilibria may serve to increase or decrease this.

Although NH_3 emissions tend to increase with soil pH, there is a strong interaction between the fertiliser and the soil solution which may (e.g. for urea) override the effects of initial soil pH through hydrolysis and precipitation reactions. Important in this regard is the effect of the soil cation exchange capacity (CEC): large soil CEC (more specifically, high NH_4^+ retention) tends to reduce NH_3 volatilisation potential by reducing the concentration of NH_4^+ in the soil solution by adsorption of NH_4^+ on the exchange sites.

The ambient soil pH results in the establishment of a bicarbonate–carbonate equilibrium with dissolved carbon dioxide (CO_2):

$$CO_2\ (aq, g) \leftrightarrow H_2CO_3\ (aq) \leftrightarrow HCO_3^-\ (aq) + H^+\ (aq) \leftrightarrow CO_3^{2-}\ (aq) + 2H^+\ (aq) \qquad (A1.3)$$

In acidic soils, this equilibrium lies to the left, so that the concentration of free carbonate ions (CO_3^{2-}) is negligible. However, in alkaline (calcareous) soils, the $CaCO_3^-$ solubility equilibrium also becomes important:

$$Ca^{2+}\ (aq) + CO_3^{2-}\ (aq) \leftrightarrow CaCO_3\ (s) \qquad (A1.4)$$

It is apparent that the addition of soluble Ca^{2+} will move this equilibrium (A1.4) to the right, reducing the concentration of CO_3^{2-} in solution, thus generating additional H^+ ions (i.e. reducing the pH) via

the equilibrium shown in Equation A1.3. Furthermore, the addition of any other ion that forms sparingly soluble salts with Ca^{2+} (e.g. sulphate) will act in the opposite manner by reducing the concentration of Ca^{2+} ions and hence increasing the concentration of CO_3^{2-} ions (Equation A1.4). This will move the equilibrium (Equation A1.3) to the right and reduce the concentration of H^+ ions and increase the pH.

Meteorological conditions and time of application in relation to crop canopy development (Holtan-Hartwig and Bøckmann, 1994; Génermont, 1996) also have an influence.

Emissions of NH_3 normally increase with increasing temperature and wind speed. However, there are many other factors that influence the emission under field conditions, and therefore the temperature dependence is often difficult to verify in field measurements.

A1.1.2 Tier 1 and 2 emission factors

Global data on NH_3 emissions from synthetic fertilizers were collated by Aarhus University, the Thünen Institute and Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL). Data were collated for all urea and ammonium-based N fertilisers. However, insufficient data were found for anhydrous and aqueous NH_3. Based on the limited data available, an emission factor of 20 g NH_3 (kg N applied)$^{-1}$ was adopted.

The models developed consisted of a base model and a number of supplementary models that analysed the extent to which other explanatory variables could explain the variation in the residual variance from the base model. To reduce the number of parameters and improve their accuracy, the fertilizers were grouped into four categories:

- urea+: fertilizers where the main component was urea
- UAN: Urea ammonium nitrate
- ammonium+1: Fertilizers where ammonium was the only N source
- ammonium+2: Fertilizers containing ammonium and nitrate N.

The base model had the following explanatory variables:

- fertilizer type (as above)
- fertilizer application method (broadcast, sprayed, injected)
- ammonia measurement method (Micrometeorological, 15N, Closed chamber, Drager-Tube, Semi-open chamber, Ventilated chambers, and Wind tunnel)
- location of experiment (indoor or outdoor).

There were significant differences in the NH_3 emissions among fertilizer types, application method and indoor versus outdoor. There was no significant difference among measurement methods.

For subsequent models, the addition explanatory variables were investigated:

- application rate
- soil pH
- % clay content of the soil
- soil organic carbon content

- soil cover (bare soil, arable, grassland)
- air temperature and rainfall (tested together, in case of an interaction)

Including the application rate did not explain significantly more of the variance (there was a non-significant positive trend).

Including whether the soil had a normal pH (<7.0) or high pH (above 7.0) explained significantly more of the variance. There was a significant interaction between fertilizer type and soil pH.

Including the % clay in the soil explained significantly more of the variance.

Including the soil organic carbon concentration did not explain significantly more of the variance.

Including the soil cover (bare, arable, grassland) did not explain significantly more of the variance.

Including both the air temperature and rainfall during the experiment found a significant effect of rainfall but not of temperature or of the interaction between them.

Choice of model for Tier 2 methodology

The choice of which models on which to base the emission factors in the Tier 2 methodology was made using the following criteria:

- The base model because it included the major factors determining emissions.
- The additional explanatory variable(s) must account for a significant proportion of the residual variance from the base model.
- For continuous variables, the slope of the regression must be such that including it in the methodology would materially improve the accuracy of the emission estimate.
- Data for the explanatory variable is likely to be available to emission inventory compilers with sufficient quality (i.e. the increase in accuracy due to the inclusion of the explanatory variable would not be offset by the inaccuracy of the data)

We chose to establish emission factors in the Tier 2 methodology on the base model + soil pH. For the base model, we parameterised the model for the outdoors, broadcast application and the micrometeorological measurement method (considered the gold standard). We chose not to use other models that accounted for a significant proportion of the variance, because they did not fulfil the criteria described above.

The Tier 1 EF has been derived as a mean of default EFs for individual N fertilisers weighted according to their use based on consumption data for 2019 for Western, Central and Eastern Europe and Central Asia from the IFA (https://www.ifastat.org/), the proportions of the European agricultural land with a soil pH of less than or more than 7.0 (EU27 + CH + UK) and the relevant Tier 2 EFs.

Table A1.1 Consumption of N fertilizer, correspondence between IFA and base model categories and the derivation of the Tier 1 emission factor.

IFA fertilizer category			**Tier 2 EF norm pH**	**Tier 2 EF high pH**	**Tier 2 EF norm pH**	**Tier 2 EF high pH**	**Weighted average***

	Consumption (% of total N)	Category in base model	NH_3-N % of N applied	NH_3-N % of N applied	g/kg N	g/kg N	
Ammonia dir. applic.	1	none			20	20	0.2
Ammonium nitrate	28	ammonia+2	2.0	4.3	24	52	7.3
Ammonium sulphate	4	ammonia+1	6.9	15.4	84	187	3.3
Calc. amm. nitrate	15	ammonia+2	2.0	4.3	24	52	4.0
Nitrogen solutions	13	UAN	7.2	13.3	87	161	11.9
Other N straight	4	ammonia+1	6.9	15.4	84	187	3.5
Urea	20	urea+	16.1	17.0	195	206	39.5
Ammonium phosphate	4	ammonia+1	6.9	15.4	84	187	3.6
N K compound	0	ammonia+2	2.0	4.3	24	52	0.1
N P K compound	10	ammonia+1	6.9	15.4	84	187	9.7
Other NP	2	ammonia+1	6.9	15.4	84	187	1.6
Total	100					Tier 1 EF	84.6

* The proportion of agricultural soil with a pH >7.0 was 0.093 (Greve, pers. comm.)

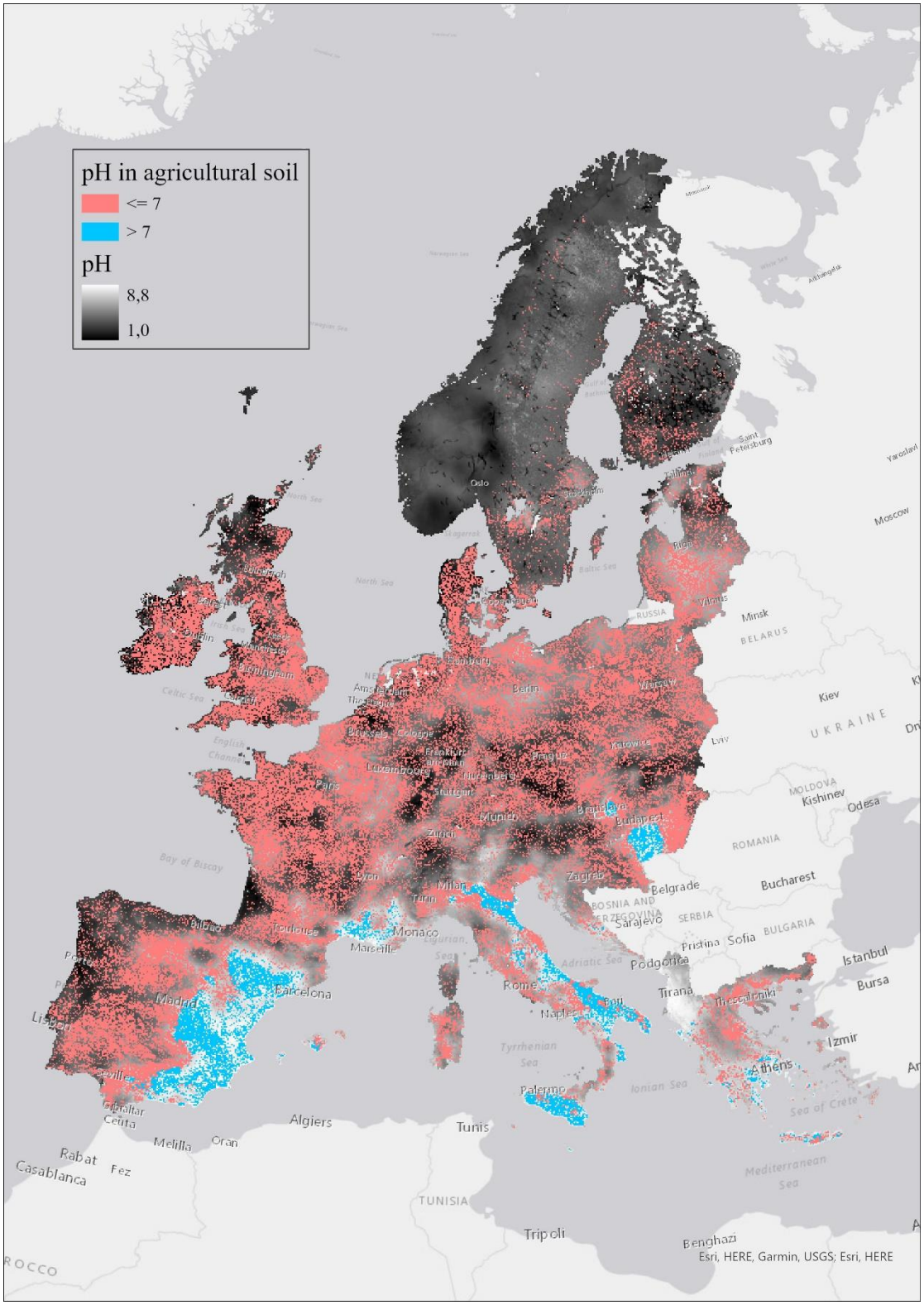

Fig A1 Distribution of pH in agricultural soils in EU27 + CH + UK.

The emissions associated with rice cultivation were not included in the analysis, as many recent reports from empirical experiments are in Chinese. Until such time as these reports can be accessed, the guidance concerning rice remains as it was in the 2019 version of the Guidebook (below).

Results from Japan (Hayashi et al., 2006) suggest that the large losses usually reported from paddy fields may be a consequence of high temperatures and not therefore directly applicable to production in more temperate regions. Furthermore, an application rate also affects the EF for urea: 21 % with a rate of 30 kg N ha^{-1} at panicle formation and reduced to 0.5 % with a rate of 10 kg N ha^{-1} at heading, in which the rice plants' effect on net exchange was included (Hayashi et al., 2008). It was estimated that rice plants accounted for c. 70 % of the NH_3 emissions from a rice paddy at the panicle formation stage after broadcast application of urea with a rate of 30 kg N ha^{-1}. In consideration of the reduced emissions from application at panicle initiation and the practice of applying much of the fertiliser N at that stage, an EF of 22 % for urea was recently proposed by Yan et al. (2003). The same EF was used for AS.

Development of Tier 1 methodology for ammonia emissions from sewage sludge

Sewage sludge is generated in sewage treatment works. The primary function of such works is to remove biologically degradable organic matter from wastewater, in order to prevent pollution of freshwater and coastal marine ecosystems. The sources of N in sewage are domestic sewage (human excreta, food waste, etc.) and industrial effluent, with the former accounting for about 93 % of treated sewage (Leip et al., 2011). Leip et al. (2011) estimated that only about 1 % of the N entering the sewage treatment system was applied to land in sewage sludge. Rose et al. (2015) estimated that the mean excretion of N by human adults was 11 g $capita^{-1}$ day^{-1} in urine and 1.8 g $capita^{-1}$ day^{-1} in faeces, resulting in an annual excretion of 4.67 kg $capita^{-1}$ a^{-1}. If the domestic contribution is assumed to be 93 % of the total, the total input of N to the wastewater treatment system is 5.0 kg $capita^{-1}$ a^{-1}. The N applied to land in sewage sludge is, therefore, estimated to be 0.05 kg $capita^{-1}$ a^{-1}.

The NH_3 emission from field-applied sewage sludge occurs from the NH_4^+ fraction. This fraction accounts for < 10 % in solid sludges and from 5 to 50 % in liquid sludges. The proportion of this NH_4^+ that is emitted as NH_3 will vary considerably, depending on the application technique and the weather at the time of application. As a first approximation, we will assume that one-third of the N in the sludge is in the ammoniacal form and that one-third of this is lost as NH_3. After converting from NH_3-N to NH_3, this yields an EF of 0.13 kg NH_3 (kg N applied)$^{-1}$.

Multiplying 0.0502 kg N applied $capita^{-1}$ a^{-1} by 0.132 kg NH_3 (kg N applied)$^{-1}$ yields an EF of 0.0066 kg NH_3 $capita^{-1}$ a^{-1}. The Tier 1 methodology is therefore:

NH_3 emission from sewage sludge applied to land = 0.0066 × human population

Note that by using total population rather than adult population, the NH_3 emission may be overestimated. However, given the other uncertainties in the development of the methodology and the limited extent to which this source will contribute to national NH_3 emissions, it is not worth attempting to refine the methodology further.

Development of Tier 2 methodology for ammonia emissions from crop residues

The methodology is based on the regression model developed by de Ruijter and Huijsmans (2019) to calculate NH_3 emissions from crop residues for the NH_3 Inventory of The Netherlands. This methodology was developed for a temperate climate and since moisture greatly affects NH_3 volatilization a separate EF for semi-arid climates should be derived. Nevertheless, the methodology is generally considered transferable to other cropping systems and regions providing sufficient information is available on the properties of crop residues. Hence in the methodology provided here

crop residue N contents are derived from IPCC (2019) defaults. However, given the limited number of residues for which IPCC provide information, the table of crop residue contents provided by de Ruijter and Huijsmans (2019) is given below in Table A1.3. These data may be broadly applicable to crop residues grown in other regions with a cool maritime climate and where manure and ferilizer N applications are comparable to those applied in The Netherlands. However, Parties need to take account of N applications to crops in The Netherlands generally being greater than in most other countries (World Bank, 2023). The results presented by de Ruijter and Huijsmans (2019) were averages derived from literature data and the authors acknowledged that for individual situations the values may differ. The amount of crop residue and its N content depend on the production goal of the crop, harvest period (early or late in the growing season), as well as by soil fertility and vigor of growth (Feller et al., 2011, cited in de Ruijter and Huijsmans, 2019). For green manure crops, the amount of residue is greatly influenced by sowing time and growing conditions in autumn. The effect of end use can be illustrated with carrots. For the production of bunch carrots, entire plants are harvested, whereas for the production of washed carrots the foliage remains on the field. Hence in table A1.3 two carrot crops are reported.

Table A1.3 Nitrogen content of crop residues (g/kg dry matter) from de Ruijter and Huijsmans 2019.

Crop	N content (g/kg dry matter)
Grass and forage crops	
Pasture topping	29
Grassland area mown	15
Grassland renovation	24
Alfalfa	27
Silage maize	7.
Fodder beet	33
Cereals	
Winter wheat	6
Spring wheat	6
Winter barley	7
Rye	5
Oats	7
Grain maize	6
Generic values for other cereal grains	6
Grain legumes	
Field beans	8
Sweet corn	17
Corn Cob Mix	7
Grass seed	8
Root and tuber crops	
Potatoes	19
Total seed potatoes	32
Starch potatoes	14
Sugar beet	20

Oilseed and fibre crops	
Rape	10
Fibre flax	5.
Chicory for inulin	16
Hemp	15
Vegetables	
Onions	
Leeks	31
Washed carrots	21
Bunched carrots	16
Winter Carrots	21
Beetroot	25
Scorzonera	18
Cauliflower	36
Kale	25
Broccoli	37
Chinese cabbage	35
Green cabbage	29
Red cabbage	30
Conical cabbage	27
Sprouts	21
White cabbage	24
Peas	24
French beans	26.0
Broad beans	10.7
Red kidney beans	7.2
Celery	20.8
Celeriac	23.9
Lettuce, leaf and other kinds	34.4
Lettuce, iceberg	38.3
Chicory	22.1
Endive	28.8
Asparagus	28.8
Fennel	32.7
Spinach	42.4
Courgettes	37.5
Other vegetables	26.9
Strawberries (horticultural)	15.2
Greeen manures	
Fodder radish	23.0
Yellow mustard	21.0
Brassica	21.0
Perennial ryegrass	28.0
Italian ryegrass	22.0

'Westerwolds' ryegrass	22.0
Winter rye	32.0
Red clover	32.0
White clover	35.0
Persian clover	30.0
Vetch	40.0
Facelia	31.0
Tagetes patula	19.0
Green manure after maize	39.0
Foliage residues	
Dahlia	10.5
Gladiolus	11.3
Hyacinth	17.3
Iris	11.9
Crocus	12.6
Lily	11.0
Daffodil	10.0
Tulip	11.0
Zantedeschia	11.9
Other flower bulb or tuber crops	11.9
Flower residues	
Dahlia	25.5
Gladiolus	23.3
Hyacinth	27.2
Daffodil	20.2
Tulip	23.0

For a Tier 2 EF the above calculation is carried out for each crop residue left on the soil surface for >3 days. Country-specific values of the N content of each type of residue (g kg^{-1}) may be used or if country-specific data are unavailable the IPCC default values in Table 3.3 may be used. There is also the option of using the greater number of crop-specific N contents reported by de Ruijter and Huijsmans (2019) (see Annex 3).

Crop area harvested

In their model of crop residue emissions the the national inventory of The Netherlands De Ruijter and Huijsmans (2019) used a three-year average to reduce the effect of short-term fluctuations. However, that approach was taken to develop the methodology, but since one of the purposes of a national inventory is to estimate annual emissions and any trends in those emissions, for the purposes of inventory preparation crop areas for the inventory year should be used.

Amounts of crop residues left in the field

Although de Ruijter and Huijsmans (2019) provide a crop-specific methodology to calculate the amounts of N returned to soil in crop residues, we propose users adopt the approach developed by IPCC (2019). De Ruijter and Huijsmans (2019) developed a methodology for use in preparing the national inventory of The Netherlands and hence it may be too country-specific to be used across

the UNECE area. It is also likely that GB users will already be familiar with the IPCC methodology from compiling national GHG emission inventories. More information on the method of De Ruijter and Huijsmans (2019) is given here should any Party wish to consider whether their method may give a more robust estimate of NH_3 emissions from crop residues.

There is one important departure from the IPCC methodology. The IPCC method was developed to calculate emissions of N_2O which arise from below the soil surface. Hence IPCC (2019) estimates the amounts of N in below-ground residues. In contrast the methodology proposed here, based on that of de Ruijter and Huijsmans (2019), only considers residues remaining on the soil surface to be a source of NH_3 emissions. Hence in the methodology used here the IPCC calculations have been amended to omit below-ground residues and any above-ground residues incorporated within 3 days.

De Ruiter and Huijsmans (2019) give a very comprehensive list of amounts of crop residues typically left in the field and their N concentrations (Table A1.3), together with N loads in crop residues (kg ha^{-1}) considered appropriate for The Netherlands together with 'contributing fractions', i.e. the proportions of post-harvest residues likely to remain on the soil surface for > 3 days in The Netherlands. Parties should attempt to derive these data for their own country. The values reported by de Ruiter and Huijsmans (2019) could be used as defaults in the absence of national data or to provide comparison with national data that are available.

IPCC (2019) advises that with regard to crop residue N, a cross check with the amount of NbeddingMS of the Equation 10.34 in "Managed manure N available for application to managed soils, feed, fuel or construction use" (Volume 4, Chapter 10 Section 10.5.4) and "Field Burning of Agricultural Residue" (3F CRF category – Volume 4, Chapter 5 Section 5.2.4), relative to the amount of agricultural residues that is returned to soils other than the amount of agricultural residues that is removed for other purposes (e.g. bedding) or burnt should be done, in order to eliminate the possibility of double counting.

Correction factor to correct for limited exposure to air of crop residues after harvest
Emission calculations need to take account of the proportion of crop residues incorporated before all NH_3 volatilization has taken place. De Ruijter et al. (2013; cited in de Ruijter and Huijsmans, 2019) used expert consultation to estimate F, the degree of incorporation of crop residues into the soil, either during harvest or because of soil tillage. F indicates the degree of exposure to air of the crop residues.

0 = incorporation within 3 days after harvest and hence no contribution to emissions
0.5 = half of the residues is covered or mixed with soil at harvest.

1 = No covering by soil during harvest or incorporation.

Green manure crops

For NH_3 volatilization from residues of green manure crops, F was based on frost sensitivity since NH_3 volatilization from green manure crops arises from crops that are sensitive to frost and not yet incorporated before frost occurs, and by green manure crops that are killed by herbicides. De Ruijter and Huijsmans (2019), based on the characteristics of green manure crops reported by Timmer (2003; cited by De Ruijter and Huijsmans, 2019) developed F factors for those green manure crops. Green manures were divided into two groups according to their degree of frost sensitivity. Half of

the frost-sensitive green manure crops grown in The Netherlands are estimated to be incorporated into the soil before senescence and hence that fraction of the crop will not leave residues on the surface and emit NH_3. The 50% of frost-sensitive crops that are not incorporated will emit NH_3 after being killed by frost giving a F factor of 0.5. Between 10 and 25% of frost tolerant crops are estimated to be killed by herbicide application, with the remainder being incorporated. In their study de Ruijter and Huijsmans (2019) used 19% as the average proportion of frost-tolerant green manure crops killed by herbicide. Table A1.4 below gives the F factors for the green manure crops evaluated by de Ruijter and Huijsmans (2019).

Table A1.4 F factors for the green manure crops evaluated by de Ruijter and Huijsmans (2019)

Green manure crop	F, fraction of crop potentially emitting NH_3
Fodder radish	0.50
Yellow mustard	0.50
Brassica	0.19
Perennial ryegrass	0.19
Italian ryegrass	0.19
'Westerwolds' ryegrass	0.19
Winter rye	0.19
Red clover	0.50
White clover	0.19
Persian clover	0.50
Vetch	0.50
Facelia	0.50
Tagetes patula	0.50

The above values were derived from work carried out in The Netherlands so will not be directly relevant for other Parties. However, the principles followed by de Ruijter and Huijsmans can be followed for green manure crops grown in other countries and where no data are available the above values may be used until country-specific data become available.

1. de Ruijters and Huijsmans paper.
2. https://edepot.wur.nl/213704
3. https://edepot.wur.nl/290558

The publications 2 and 3 are open access, with publication 3 containing F values (see Table 2.2).

Tier 1 emission factor

The amount of N in crop residues on the soil surface from which NH_3 may be emitted is calculated from the mass of crop residues deposited on the soil surface, the concentration of N in those residues and the proportion of these crop residues that contribute to NH_3 emission.

$EF = ((0.41 * \text{N concentration in crop residues (g kg}^{-1}) - 5.42) * F_T$

To create a Tier 1 EF as a proportion of crop residue N applied two default values are needed.
First, an average value of the N concentrations in crop residues > 13.2 given in Table 3.3. This is 20 g kg^{-1}.

Second a value for the contributing factor of crop residues, F_T i.e. the proportion of the crop residues left on the soil surface for > 3 days. For use in the Tier 1 EF this proportion is taken as 1.

This gives a Tier 1 EF of:
((0.41 * 20) - 5.42) *1/100

= 0.028 of crop residue- or green manure-N left on the soil surface for > 3 days emitted as NH_3-N

= 0.034 kg NH_3 per kg crop residue left on soil surface for > 3 days.

Annex 2 Nitric oxide

A2.1 Overview

Soils and crops are considered to be a net sink for most NO_x (NO plus NO_2) compounds. However, NO may be released from soils during nitrification and denitrification after N application and mineralisation of incorporated crop residues and soil organic matter. Estimates of NO emissions are very uncertain, but soils may contribute c. 4–8 % of total European emissions. On a hot summer day, this fraction may increase to values of > 27 % (Stohl et al., 1996; Butterbach-Bahl et al., 2001). On the global scale, estimates consider that NO_x emissions from soils could represent more than 40 % of NO_x emissions (Penner et al., 1993; Davidson and Kingerlee, 1997) and up to 65 % for the USA (Hall et al., 1996).

A2.2 Description of sources

A2.2.1 Process description

While NO is also a substrate and product of denitrification, it is only very rarely emitted as a consequence of denitrification in European soils (see Ludwig et al. (2001) for further details).

A2.2.2 Emissions

Data on NO emissions in relation to fertiliser N use were reviewed by Yienger and Levy (1995) and were updated by Skiba et al. (1997). Yienger and Levy (1995) calculated an arithmetic mean emission of 2.5 % loss of fertiliser N. Based on almost the same data set, Skiba et al. (1997) showed that NO losses ranged from 0.003 to 11 % of applied fertiliser N with a geometric mean emission of 0.3 %. More recently, Bouwman et al. (2002a) used the residual maximum likelihood (REML) technique to calculate, from 99 studies of NO emissions, a global mean fertiliser-induced NO emission of 0.7 %. Before this, an EF of 1.0 % of applied N was suggested by Freibauer and Kaltschmitt (2000).

Maljanen et al. (2007) reported emissions of NO from grazed pastures that were c. 40 % of those of N_2O; background emissions were c. 25 % of N_2O. NO emissions increased with increasing soil temperature and with decreasing soil moisture. Emissions of NO are still poorly understood, but it is clear that there are differences in the mechanisms regulating N_2O and NO production. There are not enough data available to discuss the effect of grazing on NO emissions, but the localised very high N and C inputs caused by animal excreta are likely to stimulate NO production.

A2.2.3 Controls

In temperate climates, NO emissions are considered to be predominantly a consequence of nitrification. Hence, substitution of AN for urea to reduce NH_3 emissions, may also give some reduction in NO emissions; the results from Slemr and Seiler (1984) are consistent with this hypothesis. Nevertheless, these conclusions can only be tentative as there are insufficient data to discriminate among fertiliser N sources (Skiba et al., 1997). Chu et al. (2007) reported that the use of controlled-release urea fertiliser could reduce emissions of NO.

A2.3 Methods

The Tier 1 methodology for sewage sludge is calculated by multiplying the EF derived from Stehfest and Bouwman (2006) of 0.04 kg NO_2 (kg N applied)$^{-1}$ by the estimate of 0.05 kg N applied capita^{-1} a^{-1}, derived in Equation A1.2. The result is 0.002 kg NO_2 capita^{-1}.

There is currently no Tier 2 methodology for NO.

A2.4 Data quality

A2.5 Uncertainty assessment

Less information is available on the factors that determine losses of NO from soils (N input, soil temperature and soil moisture, soil texture, soil C). Long-term intensive field experiments are not currently sufficient to provide a good degree of certainty in the estimate. The data available suggest that the EF for NO is broadly similar to the EF for N_2O (Bouwman et al., 2002a; Stehfest and Bouwman, 2006).

A2.6 Gridding and temporal disaggregation

Losses of NO take place mainly as a consequence of nitrification and in acid soils as a consequence of chemo-denitrification. Peaks in NO emission are therefore likely after the application of NH_4^+-based N fertilisers, incorporation of crop residues and tillage of soils. Data on all of these processes should be available, for some countries at least. At present, however, there are insufficient data on NO emissions to quantify these effects. Ultimately, as the mechanisms of NO production become better understood, climatic data may also be utilised to assess when soil and weather conditions are favourable for nitrification, and hence NO production (Butterbach-Bahl et al., 2004). In common with NH_3, NO emissions may vary greatly in space and time from year to year, depending upon weather conditions and fertiliser input.

Annex 3 Non-methane volatile organic compounds

A3.1 Description of sources

A3.1.1 Emissions

Hewitt and Street (1992) concluded that trees are the main emitters of non-methane hydrocarbons (NMHCs). Other plants, including crops, were insignificant sources in comparison. However, although NMVOC emissions from plant production and agricultural soils are smaller than from woodlands, they may not be entirely negligible (Simpson et al., 1999). König et al. (1995) noted that in earlier studies, NMHCs were regarded as the major component of VOC emissions. However, König et al. (1995) found oxygenated VOCs to be the major type of VOC emission from cereals. In that study, emissions were not invariably greater from trees than from agricultural crops.

The emission of some NMVOCs may be of benefit to plants, e.g. to attract pollinating insects, while others may be waste products or a means of losing surplus energy (Hewitt and Street, 1992). Ethene emissions have been observed to increase when plants are under stress.

As with forest NMVOC emissions, biogenic emissions from grasslands consist of a wide variety of species, including isoprene, monoterpenes (α-pinene, limonene, etc.) and oxygenated volatile organic compounds (OVOCs). The OVOC species consist of a large number of oxygenated compounds (alcohols, aldehydes, etc.) and have proven difficult to quantify in atmospheric samples. Progress in the quantification of OVOCs from European vegetation has been made (König et al., 1995), although many more measurement data will be required before reliable attempts to specifically inventory OVOCs can be made.

Factors that can influence the emission of NMVOCs include temperature and light intensity, plant growth stage, water stress, air pollution and senescence (Hewitt and Street, 1992).

Methodologies and emission factors

The EFs include partial EFs for isoprene, terpenes, alcohols, aldehydes, ketones, ethers and other organic compounds, and their contribution to overall emissions.

The use of the following equation and data is recommended:

$$E_{NMVOC\_crop} = \sum A_i \times m_{D\_i} \times t_i \times EF_i \qquad (A3.1)$$

where E_{NMVOC_crop} is the NMVOC emission flux from cropped areas (kg a^{-1} NMVOC); A_i is the area covered by $crop_i$ (ha a^{-1}); m_{D_i} is the mean dry matter of $crop_i$ (kg ha^{-1} a^{-1}); t_i is the fraction of year during which $crop_i$ is emitting (in a a^{-1}); and EF_i is the EF for crop i (kg kg^{-1} NMVOC).

NMVOC measurements made by König et al. (1995) are used to provide information on the order of magnitude of NMVOC emissions from growing crops. Other comparable NMVOC emission studies are Lamb et al. (1993) and Winer et al. (1992).

Comparisons of the reference EFs show that the EF for wheat estimated by König et al. (1995) is significantly smaller than that estimated by Lamb et al. (1993) and Winer et al. (1992). The opposite is the case for rye: the EF estimated by König et al. (1995) is considerably greater than that estimated by Lamb et al. (1993) and Winer et al. (1992). König et al. stated that the reason for the large

difference in the emission rates between rye and wheat observed in the study is unclear. However, different stages of development might explain the differences in the observed emission rates. Rye was sampled at near blossoming stage, during which the emissions are greater and this could explain why the EF was greater than the EF suggested by the results of Lamb et al. (1993). It might be that the emissions of alcohols in the non-blossoming rye were already a result of the development of the blossoming stage. The samples for wheat were taken 3 days after blossoming and the blossoms had been washed off by heavy rain during the days prior to sampling. It might be possible that the emission of alcohols is reduced after rainfall because of the leaching of water-soluble compounds during rainfall.

Alternative derivation of Tier 1 emission factors

A Tier 1 NMVOC EF can be determined if the data in Table 3.5 (Section 3.4) are combined with some additional data (average crop yield, dry matter content and crop areas).

Yield and dry matter content vary significantly from country to country because of differences in climatic conditions and the use of agricultural technology. If country-specific yield and dry matter contents are not available, the following can be used.

- Average crop yields can be estimated from FAO agricultural statistics, which include data on the main crop-producing countries in the European Monitoring and Evaluation Programme (EMEP) area (FAO, 2012). Yield values are based on the 2006–2010 average. Dry matter content is assumed to be 0.85 kg per kg harvested for wheat and rye, 0.90 kg per kg for rape and 0.30 kg per kg for grass. The yield for grassland is based on Danish agricultural conditions because no yield data for grass are given in FAO Statistics.

Crops emit NMVOCs during the growing season only. For the purposes of this methodology, the growing season accounts for 0.3 of the year for wheat, rye and rape, while the fraction of the year for grassland is taken as 0.5 (Rösemann et al., 2011).

Crop area data are required for different crop types, as outlined below.

- To determine the Tier 1 EF, it was necessary to aggregate the data for the different crop types. To do this, it was necessary to assume the distribution between crops and grassland. This distribution varies considerably among countries — for example, grain accounts for 55 % of the total agricultural area in Denmark, 30 % in France and 20 % in the Russian Federation. The distribution of the fraction of wheat, rye, rape and pasture land is based on estimates from data in the FAO agricultural database. An area distribution of 50 % cereals and 50 % of pasture land has been assumed.
- Two different NMVOC emission estimates are given for wheat (Table 3.5). The emission reported by König et al (1995) is much less than that suggested by Lamb et al. (1993), and thus an average emission is used. The same is true for rye, for which an average of the two emissions estimates is used. The emission from grass is based on König et al. (1995).

Based on the abovementioned assumptions, the Tier 1 NMVOC EF was determined to be 0.86 kg NMVOC per hectare per year.

A3.2 Data quality

A3.2.1 Uncertainty

The small number of measurements of NMVOC emissions from agricultural vegetation is a considerable weakness, and, in addition, the reference material is very dated. However, the literature does not appear to contain relevant studies that are more recent than those used here. It is unknown whether or not emissions are related to fertiliser N inputs.

A3.3 Uncertainty assessment

A3.3.1 Emission factor uncertainties

Biogenic VOC emissions for the United Kingdom were summarised by Hewitt and Street (1992). These ranged from 38–211 Gg a^{-1} total NMVOCs. Emissions from woodlands were estimated to be 72 % of total biogenic emissions by Anastasi et al. (1991). Thus, between c. 10 and 59 Gg a^{-1} appear to be of agricultural origin. In their incomplete analysis, Hobbs et al. (2004) calculated c. 5 t a^{-1} from agricultural crops. This compares with the Corinair 94 estimate of only 2 Gg a^{-1} for SNAP code 1001, Cultures with fertilisers, NFR 3.D.1, or < 2 % of emissions from agriculture and forestry. Thus, the range of emissions may be uncertain by a factor of 30. However, the estimate for agriculture by Anastasi et al. (1991) was recognised as likely to be too large.

A3.3.2 Activity data uncertainties

With respect to national data on crop areas, an uncertainty of < 5 % is assumed, with a normal distribution.

Annex 4 Particulate matter

A4.1 Methods

A4.1.1 Tier 1 default approach

The EFs for PM_{10} and $PM_{2.5}$ can be determined in a number of different ways, as outlined below.

- Direct measurements can be made with pre-separators. These pre-separators split the sample air flow into different components based on the aerodynamic properties of the particulate material. These measurements can be used directly for comparison or balancing.
- The PM size distribution of the total dust emissions can be measured. If total dust emissions are known, then EFs for the different PM fractions can be determined.
- It is also possible, based on measurements, to calculate the different PM fractions as a proportion of the TSP. To get results comparable with other approaches, the definition and measuring procedure for TSP must be known.

Takai et al. (1998) introduced a sampler for the 'inhalable part' of TSP. These samplers have a cut diameter (50 % separation) at 100 µm.

A literature review reported different ways to create EFs for arable farming.

- Direct measurements of the primary PM emissions from the use of cultivation implements can be used. From these, machinery-related estimates of the potential strength of a source and field-related EF may be calculated.
- Indirect estimations of source strength using concentration measurements carried out using machinery placed in the driver's cab and a layer- or plume-based model of the treated area to establish a relationship with the balance volume or volume flow rate concerned can be made.
- Measurements of PM concentrations at the border of a field fitted to an inverse computing model of dispersion can be used.

The PM_{10} EFs given below were reported.

Combine harvesting:

- 4.1–6.9 kg ha^{-1}, parameter cereal, cereals humidity during harvesting (Batel, 1976)
- 3.3–5.8 kg ha^{-1} (WRAP, 2006).

Because of the settling effect of coarse particles, it was assumed that only part of the primary emitted PM_{10} leaves the field to give the field EF. Two situations have been considered: one with 50 % of the original PM_{10} emissions leaving the field and one with 10 % leaving the field.

Soil cultivation:

- 0.1 kg ha^{-1}, the Regional Air Pollution Information And Simulation (RAINS)
- 0.06–0.3 kg ha^{-1} (Wathes et al., 2002)
- 0.28–0.48 kg ha^{-1} (Hinz, 2002).

Assumptions based on both models are not consistent with measured values and lead to overestimates of EFs. Corrections gave an averaged field EF of 0.25 kg ha ha^{-1} as given in the matrix:

- 4.2 kg ha^{-1}, US National Emission Inventory (NEI) method;
- 5.2 kg ha^{-1}, US California Air Resources Board (CARB) method.

Measurements from California are much larger. This is because of the climatic and soil conditions, that is, higher temperatures and lower humidity. This is supported by measurements carried out in Brandenburg, Germany, under 2006 conditions — which were hot and dry — and emission values one order of magnitude greater than former years were derived.

Table A4.1 EFs for PM_{10}, $PM_{2.5}$ and PM_1 for field operations

	PM_{10}, kg ha^{-1}	$PM_{2.5}$, kg ha^{-1}	PM_1, kg ha^{-1}
Harrowing	0.82	0.29	< 1
Discing	1.37	0.12	0.03
Cultivating	1.86	0.06	0.02
Ploughing	1.20	0.05	0.01

Source: EFs for soil operations (van der Hoek and Hinz, 2007).

Source strength is computed using the inverse Lagrangian dispersion model aided by concentration measurements made using a particle counter. This is a first approach to calculation with some uncertainties in the model but also in measurements.

A4.1.2 Default emission factors

Table A4.2 PM EFs (EFPM) for agricultural crop operations, in kg ha^{-1} PM (van der Hoek and Hinz, 2007)

Crop	Soil cultivation	Harvesting	Cleaning	Drying
Wheat	0.25	2.7	0.19	0.56
Rye	0.25	2.0	0.16	0.37
Barley	0.25	2.3	0.16	0.43
Oats	0.25	3.4	0.25	0.66

The measured values are of emissions from the immediate surroundings of the tractors and harvesting machinery in the field.

Further information about PM emissions can be found in Hinz and Funk (2007) and Hinz and Tamoschat-Depolt (2007).

A4.2 Data quality

A4.2.1 Completeness

The small number of measurements of PM emissions from agricultural activities is a considerable weakness.

Annex 5 Summary of updates

Table A5.1 Summary of updates to calculation methodologies and EFs made during the 2023 revision of this chapter

Emission	Tier 1		Tier 2	
	Methodology	EFs	Methodology	EFs
NH_3	**Updated**	**Updated**	**Updated**	**Updated**
NO	Not updated	Not updated	**Updated**	Not updated
NMVOC	Not updated	Not updated	NC	NC
PM	Not updated	Not updated	Not updated	Not updated

NC, not calculable.

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