European Environment Agency

| Category | | Title |
|---|---|---|
| **NFR** | **3.B** | Manure Management |
| | 3.B.1.a, 3.B.1.b, 3.B.2, 3.B.3, 3.B.4.a, 3.B.4.d, 3.B.4.e, 3.B.4.f, 3.B.4.g.i, 3.B.4.g.ii, 3.B.4.g.iii, 3.B.4.g.iv, 3.B.4.h | |
| **SNAP** | 100901 | Dairy cattle |
| | 100902 | Non-dairy cattle |
| | 100905 | Sheep |
| | 100903, 100904 | Swine (finishing pigs and sows) |
| | 100914 | Buffalo |
| | 100910 | Goats |
| | 100906 | Horses |
| | 100912 | Mules and asses |
| | 100907 | Laying hens |
| | 100908 | Broilers |
| | 100909 | Turkey |
| | 100909 | Other poultry |
| | 100911, 100913, 100915 | Fur animals, Camels, Other Animals |
| **ISIC** | | |
| **Version** | Guidebook 2019 | |

*Under NFR reporting, ‘Fur animals’ and ‘Camels’ should be reported under 3.B.4.h ‘Other animals’.

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# Contents

# 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 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, because of the lack of disaggregation at both the temporal and geographical scales, and also because the methods proposed take only limited account of the impacts of weather on emissions, the output may not be suitable for use in other models. This limited account of the impacts of weather is a result mainly of the difficulty in obtaining sufficiently detailed activity data to enable accurate estimates to be made of the impacts of temperature and rainfall, for example, on emissions. If possible, users should develop methods to take account of the influence of more detailed activity data. 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) are involved 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.

Emissions of $NH_3$, NO and NMVOCs arise from the excreta of agricultural livestock that are deposited in and around buildings housing livestock and collected as liquid slurry, solid manure or litter-based farmyard manure (FYM). In this chapter, solid manure and FYM are treated together as ‘solid manure’. These emissions occur from buildings housing livestock and outdoor yard areas, from manure stores, after application of manures to land and during grazing. Emissions of PM arise mainly from feed, and also from bedding, animal skin or feathers, and occur from buildings housing livestock. Emissions of nitrous oxide ($N_2O$) also occur, and are accounted for here, when necessary, for the accurate estimation of $NH_3$ and NO emissions; however, they are not reported here as $N_2O$ is a greenhouse gas.

Livestock excreta and manure account for more than 80 % of $NH_3$ emissions from European agriculture. There is, however, wide variation among countries in emissions from the main livestock sectors: cattle, pigs, poultry and sheep. This variation from country to country is explained by the different proportions of each livestock category and their corresponding nitrogen (N) excretion and emissions, by differences in agricultural practices, such as housing and manure management, and by differences in climate.

NO emissions are converted to $NO_2$ and reported together with $NO_2$ emissions, as NOx. NO emissions from livestock housing, open yard areas and manure stores are currently estimated to account for only c. 0.1 % of total NO emissions (Table 1.1). There is considerable uncertainty concerning the NMVOC emissions from this source. Hobbs et al. (2004) estimated emissions from livestock production could be c. 7 % of total United Kingdom emissions and a similar proportion is currently reported by the European Monitoring and Evaluation Programme (EMEP) (Table 1.1).

Emissions from buildings housing pigs and poultry represent around 30 and 55 %, respectively, of agricultural $PM_{10}$ emissions; the remainder is mainly produced by arable farming. Emissions from livestock housing are estimated to produce c. 9 % of total $PM_{10}$ emissions.

This chapter provides guidance on the calculation of emissions from all stages of manure management, including emissions from livestock housing, open yard areas and manure stores, together with the emissions that occur after the application of manures to land and from excreta deposited in fields by grazing animals. Some of these sources are reported in Nomenclature for Reporting (NFR) 3D, Crop production and agricultural soils, but all methodologies are presented together in this chapter because the Tier 2 methodology developed to calculate $NH_3$ emissions from livestock production treats these emissions as part of a chain of sources, enabling the impact of $NH_3$ and other N emissions at one stage of manure management on the $NH_3$ emissions from subsequent sources to be estimated (see Annex 1, section A1.2). For a full description of reporting requirements see section 3.2.

In the remainder of this chapter, the comment ‘see Annex 1’ indicates that further information is provided in the annex.

**Table 1.1 Contributions from livestock production to emissions of gases**

| | $NH_3$ (a) | $NO_x$ | NMVOC | $PM_{2.5}$ | $PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Total, Gg $a^{--1}$ | 3 810 | 8 166 | 6 933 | 1 220 | 1 808 | 3 440 |
| Livestock, Gg $a^{-1}$ | 2 327 | 7 | 495 | 34 | 164 | 354 |
| Livestock, % | 61.1 | 0.1 | 7.1 | 2.8 | 9.1 | 10.3 |

Notes: The figures are 2013 estimates for EU-27.

(a)The estimates of NH3 emissions includes those from only housing, uncovered yard areas and manure stores. Emissions after manure application and during grazing are reported under NFR 3D, Crop production and agricultural soils. Gg a–1: Gigagrammes per year, NOx, nitrogen oxides; TSP, total suspended particles.

Source: http://ceip.at

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

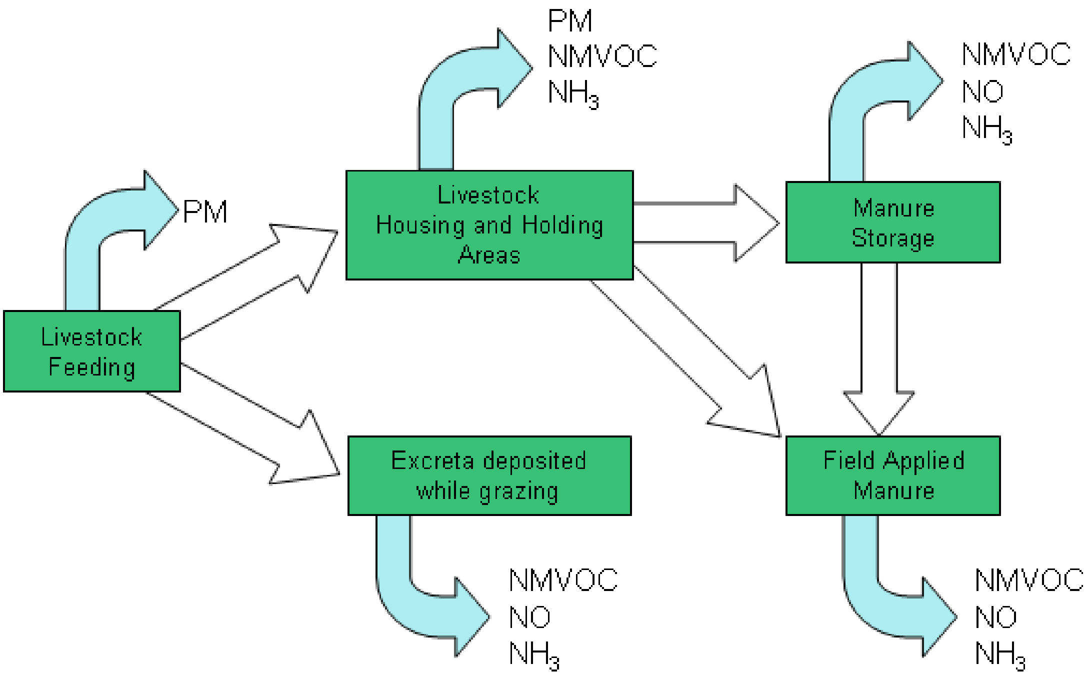
# 2 Description of sources

There are five main sources of emissions related to livestock husbandry and manure management:

- livestock feeding (PM);
- manure generated in livestock housing and on open yard areas ($NH_3$, PM, NMVOCs);
- manure storage ($NH_3$, NO, NMVOCs);
- field-applied manure ($NH_3$, NO, NMVOCs);
- excreta deposited during grazing ($NH_3$, NO, NMVOCs).

## 2.1 Process description

**Figure 2.1 Process scheme for emissions resulting from livestock feeding, livestock excreta and manure management**



### *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.

The source of $NH_3$ emissions from manure management is the N excreted by livestock.

$NH_3$ is emitted if excreta or manure are exposed to the atmosphere, namely in livestock housing, from manure stores, after manure application to fields and from excreta deposited by grazing animals (note that although the $NH_3$ emissions after manure application and from pastures grazed by livestock are calculated here, they should be reported under NFR 3D, Crop production and agricultural soils). Differences in agricultural practices, such as housing and manure management, and differences in climate have significant impacts on emissions.

Further information on the processes leading to emissions of $NH_3$ is given in annex 1, section A1.2.1.

### *2.1.2 Nitric oxide*

NO is formed initially through nitrification and subsequently also by denitrification in the surface layers of stored manure or in manure aerated to reduce odour or to promote composting. At present, few data are available on NO emissions from manure management. NO emissions from soils are generally considered to be products of nitrification. Increased nitrification is likely to occur after the application of manures and the deposition of excreta during grazing. NO emissions arising from livestock housing and manure stores should be reported under NFR 3B, while those arising after the application of manures to land or from grazed pastures should be reported under NFR 3D.

#### *2.1.3 Non-methane volatile organic compounds*

Significant emissions of NMVOCs have been measured from livestock production. In addition to manure management, silage stores are a major source and emissions occur during feeding with silage.

Sites of emission include livestock housing, yards, manure stores, fields to which manure is applied and fields grazed by livestock. Emissions occur from manure managed in solid form or as slurry. Only a limited number of studies have been undertaken on NMVOC emissions from livestock husbandry, the results of which are highly variable thus leading to large uncertainties in the emission estimates. Most of the NMVOC studies have focused on emissions from housing and on odour-related issues.

#### *2.1.4 Particulate matter*

The main sources of PM emission are buildings housing livestock, although outdoor yard areas may also be significant sources. These emissions originate mainly from feed, which accounts for 80 to 90 % of total PM emissions from the agriculture sector. Bedding materials, such as straw or wood shavings, can also give rise to airborne particulates. Poultry and pig farms are the main agricultural sources of PM. Emissions from poultry housing also arise from feathers and manure, while emissions from pig houses arise from skin particles, faeces and bedding. Animal activity may also lead to the re-suspension of previously settled dust into the atmosphere of the livestock housing (re-entrainment). Winkel et al. (2015) demonstrated that PM concentrations within a building housing pigs were considerably greater during daytime and particular periods of animal activity. It is therefore important to ensure that any emission measurements are taken over a long enough period to ensure that they are suitably representative before being scaled up to determine an annual emissions estimate.

### 2.2 Reported emissions

#### *2.2.1 Ammonia*

Estimates of $NH_3$ emissions from agriculture indicate that in Europe 60–90 % originate from livestock production (http://webdab.emep.int). The amount of $NH_3$ emitted by each livestock category will vary among countries according to the size of that category. In most countries, dairy and other cattle are the largest sources of $NH_3$ emissions. For example, in France, dairy cows account for 31 % of the total from agriculture, while other cattle account for 24 % of the agriculture total (CITEPA, 2015). In some countries, emissions from pig production may also be large, e.g. in Denmark where pig production accounts for about 40 % of emissions (Hutchings et al., 2001). Emissions from livestock categories other than cattle, pigs and poultry tend to be minor sources, although sheep can be a significant source for some countries.

It is important to consider the relative amounts of emissions from different stages of manure management. For most countries, the greatest proportions of $NH_3$ emissions from livestock production arise from buildings housing livestock and after the application of manures to land, each of which typically account for 30–40 % of $NH_3$ emissions resulting from livestock production. Emissions from storage and outdoor livestock each typically account for 10–20 % of the total. Emissions during grazing tend to be fairly small as the total ammoniacal nitrogen (TAN) in urine deposited directly on pastures is quickly absorbed by the soil. The proportion of emission from housing and after manure application will decrease as the proportion of the year spent at pasture increases.

The wide-scale introduction of abatement techniques, although reducing total $NH_3$ emissions, is likely to increase the proportions arising from housing and during grazing, since these sources are the most difficult to control. Abatement measures for land application of manures have been introduced to the greatest extent, since these are among the most cost effective. In contrast, abatement techniques for housing are often expensive and tend to be less effective.

In order to calculate $NH_3$ emissions, it is necessary to have quantitative data on all the factors noted at the beginning of this section. In practice, results may be summarised to provide 'average' emission factors (EFs) per animal housing place for each emission stage for the main livestock categories and management types, or to provide total annual EFs. Total $NH_3$ emissions are then scaled by the numbers of each class of livestock in each country.

### *2.2.2 Nitric oxide*

Very few data are available on emissions of NO from manures during housing and storage that can be used to compile an inventory. Emissions of NO-N and $N_2O$-N are estimated to quantify the N mass balance for the Tier 2 methodology used to calculate $NH_3$ emissions, and by doing so are used to estimate NO emissions during housing and storage.

### *2.2.3 Non-methane volatile organic compounds*

A list of the principal NMVOCs, from the main emission sources, and a classification of the volatile organic compounds (VOCs) according to their importance, was included in the Convention on Long-range Transboundary Air Pollution (CLRTAP) protocol in order to address reductions in VOC emissions and their transnational flows (UNECE, 1991). The CLRTAP protocol classifies NMVOCs into three groups, according to their importance in the formation of $O_3$ episodes, considering both the global quantity emitted and the VOCs' reactivity with hydroxyl radicals.

Some of the major NMVOCs released from livestock housing are listed in annex 1, section A1.2.2.

### *2.2.4 Particulate matter*

In order to calculate PM emissions in detail, it would be necessary to have quantitative data on all the factors noted in annex 1, section A1.2.2. In practice, the data available allow the use of only average EFs for each livestock sub-category.

Further information on emissions is given in annex 1, section A1.2.2.

## 2.3 Controls

### *2.3.1 Ammonia*

Descriptions of measures to reduce $NH_3$ emissions from manure management can be found online (https://www.unece.org/fileadmin/DAM/env/documents/2012/EB/ECE_EB.AIR_120_ENG.pdfhttp://www.unece.org/fileadmin/DAM/env/documents/2012/EB/N_6_21_Ammonia_Guidance_Document)_Version_20_August_2011.pdf) (Version 7 February 2014).

Chapter 3 explains how the implementation of abatement measures can be accounted for in national inventories using a Tier 3 methodology. Annex 1, section A1.4, summarises the activity data that are needed to take account of the adoption of abatement measures.

### *2.3.2 Nitric oxide*

The use of nitrification inhibitors has been proposed to reduce emissions of $N_2O$, and their use may have an additional benefit in curtailing emissions of NO.

### *2.3.3 NMVOCs*

Techniques which reduce $NH_3$ and odour emissions may also be considered effective in reducing the emission of NMVOCs from livestock manure (Annex 1, section A1.2.3). Possible ways of achieving such reductions include the immediate covering of silage stores (pits) and minimising the area of silage available to feeding animals.

### *2.3.4 Particulate matter*

Techniques to reduce concentrations of airborne dust in livestock housing have been investigated. These are summarised in annex 1, section A1.2.3.

## 2.4 Factors to be taken into account during inventory preparation

### *2.4.1 Ammonia*

When applying or developing techniques to estimate and report emissions, users need to consider that $NH_3$ emissions from livestock production depend on many factors including:

- the proportion of time spent by animals indoors and outside, e.g. at pasture or in yards or housed, and animal behaviour;
- whether livestock excreta are handled as slurry or solid;
- the housing system of the animal (especially the floor area per animal) and whether or not manure is stored inside the building.

In addition, account will need to be taken of the amounts of livestock manures used as feedstocks for anaerobic digestion (AD), as emissions from the storage of AD feedstocks are accounted for in Chapter 5B2.

The excretion of N, and the subsequent emission of $NH_3$, varies among livestock species (e.g. cattle and pigs). Within a livestock species, there are large differences among animals kept for different purposes (e.g. dairy cattle versus beef cattle). It is therefore necessary, whenever possible, to disaggregate livestock according to species and production type.

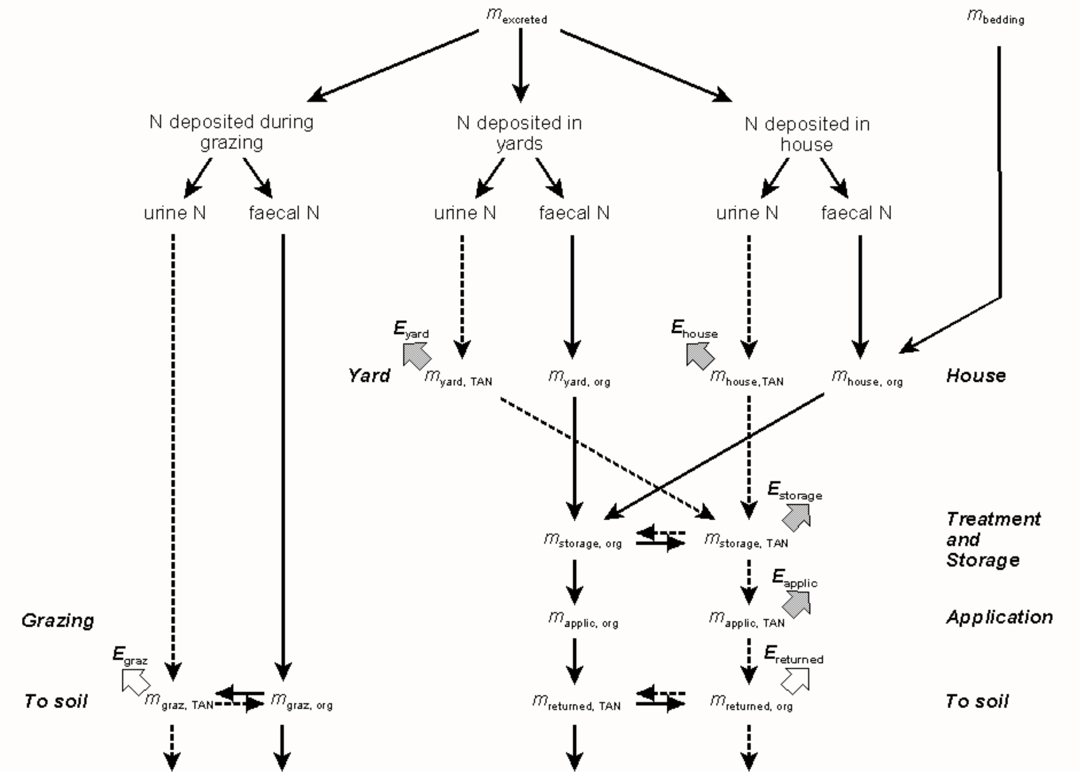
$NH_3$ emissions from livestock manures that occur during housing and storage, and as a result of field application, depend on:

- livestock category
- bedding material
- the TAN content of the excreta.

Other factors, which can be taken into account using Tier 3 methodologies, are listed in annex 1, section A1.4.

The pathways for the emission of N species are shown in Figure 2.2.

**Figure 2.2 N flows in the manure management system (Source: Dämmgen and Hutchings, 2008)**

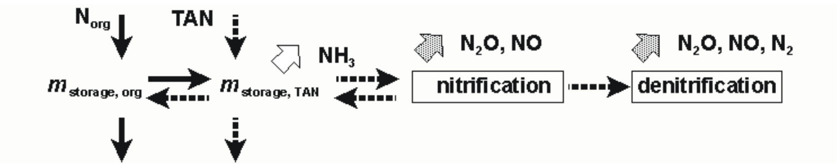


**Notes:**

Narrow broken arrows refer to TAN; narrow continuous arrows refer to organic N; *m* refers to mass from which emissions may occur. The horizontal arrows denote the process of immobilisation in systems with bedding occurring during housing, and the process of mineralisation during storage. Broad hatched arrows denote emissions assigned to manure management ($E_{applic}$, $NH_3$ emissions during and after application; $E_{hous}$, $NH_3$ emissions from livestock housing; $E_{storage}$, $NH_3$, $N_2O$, NO and di-nitrogen ($N_2$) emissions from storage; $E_{yard}$, $NH_3$ emissions from yards). Broad open arrows indicate emissions from soils ($E_{graz}$, $NH_3$, $N_2O$, NO and $N_2$ emissions during and after grazing; $E_{returned}$, $N_2O$, NO and $N_2$ emissions from soil resulting from manure input). See subsection 3.4 of the present chapter for key to variable names.

Transition between the two forms is possible, as shown in Figure 2.3. The gaseous losses occur solely from the TAN fraction. This means that in order to estimate emissions of $NH_3$ accurately it is necessary to follow the fate of the two fractions of N separately.

**Figure 2.3 Processes leading to the emission of gaseous N species from manure**



### *2.4.2 Nitric oxide*

NO may be produced during nitrification and denitrification as indicated in Figure 2.2.

### *2.4.3 Non-methane volatile organic compounds*

Over 500 volatile compounds originating from cattle, pigs and poultry have been identified, although only c. 20 compounds were considered significant by Hobbs et al. (2004) and the United States Environmental Protection Agency (US EPA, 2012), accounting for 80–90 % of the total emissions. These compounds have very different physical and chemical properties. Variations in chemical activity, water solubility and the extent to which the compounds bind to surfaces presents significant challenges for the measuring methodology which, again, may yield large uncertainties and difficulties related to the interpretation of measured data.

Emissions of NMVOCs occur from silage, manure in livestock housing, outside manure stores, field application of manure and from grazing animals. There is a lack of emission estimates related to feeding with silage, outdoor manure stores, manure application and grazing animals. The great majority of research has focused on emissions from livestock housing. The emission estimates provided here are thus based on assumed proportions of the emissions that take place during livestock housing (for a detailed explanation, please refer to annex 1, section A1.2.2).

### *2.4.4 Particulate matter*

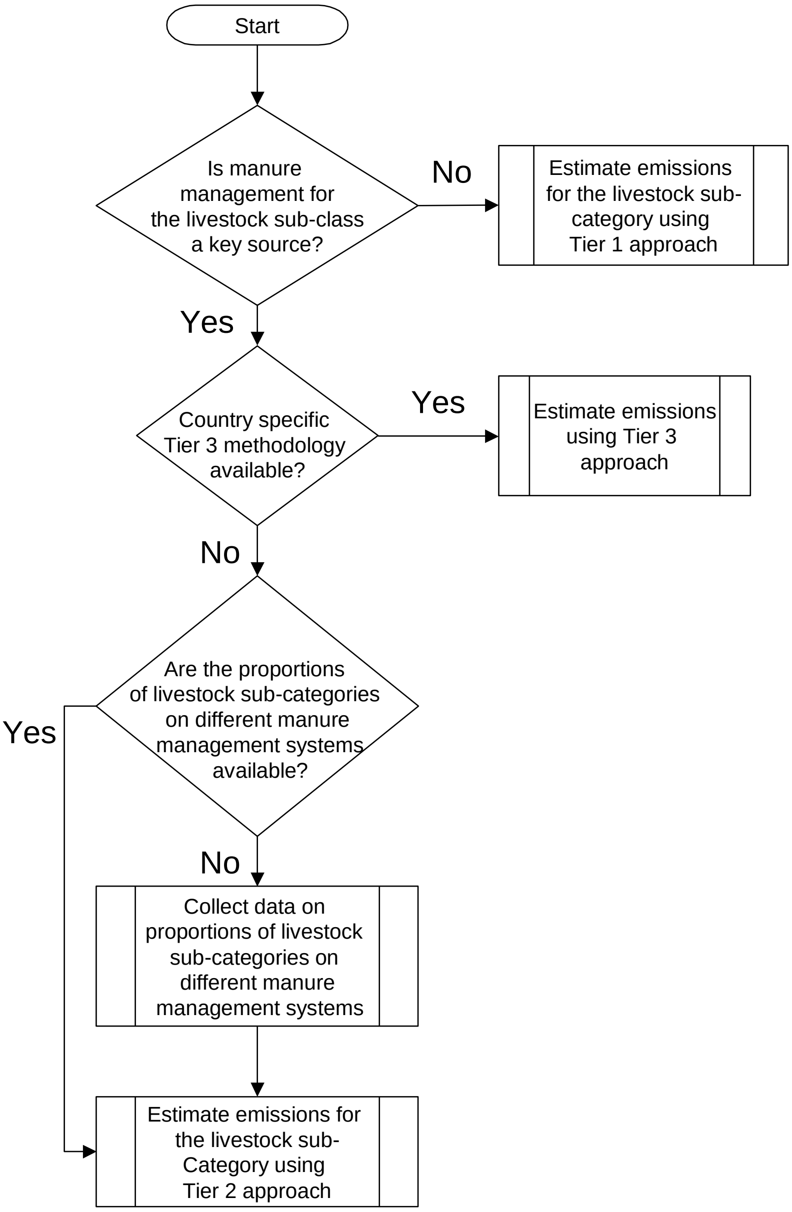
Emissions of PM occur from both housed and free-range livestock. However, the lack of available emissions measurements for free-range livestock means that the development of EFs has focused on housed livestock. Factors determining the size of PM emissions are listed in Annex 1, section A1.3.1. More data are needed on emission rates of particulates in order to better determine both mean emission rates and the variability of emission rates due to various environmental and management factors. This source is therefore also a target for prospective verification studies.

# 3 Methods

## 3.1 Choice of method

The decision tree in Figure 3.1 provides a guide to the choice of method for estimating emissions. Starting from the top left, it guides the user towards the most applicable approach.

**Figure 3.1 Decision tree for source category 3B Manure management**



General guidance on the identification of key sources can be found in part A (the general guidance chapters) of this guidebook, namely Chapter 2, *'key category analysis and methodological choice'* (EMEP/EEA, 2016). In most, if not all, countries, the main livestock categories will be key sources of $NH_3$ and it is good practice to calculate emissions using at least a Tier 2 approach for these key categories. For livestock categories that make a minor contribution to emissions, the use of a Tier 1 approach would comply with good practice requirements.

The approach is outlined below.

- If detailed information of sufficient quality is available, then it should be used.
- If the source category is a key source, it is good practice to use a Tier 2 or better method. The decision tree directs the user to the Tier 2 method, and the necessary input data with respect to N excretion and manure management systems, if the country-specific EFs needed for a Tier 3 estimate are not available.
- The use of a Tier 3 method is recommended for countries with enough data to enable the enumeration of country-specific EFs. Countries that have developed a mass-flow approach to calculating national $NH_3$-N emissions should use this approach in compliance with subsection 4.6, 'inventory quality assurance/quality control (QA/QC)'.

## 3.2 Reporting emissions

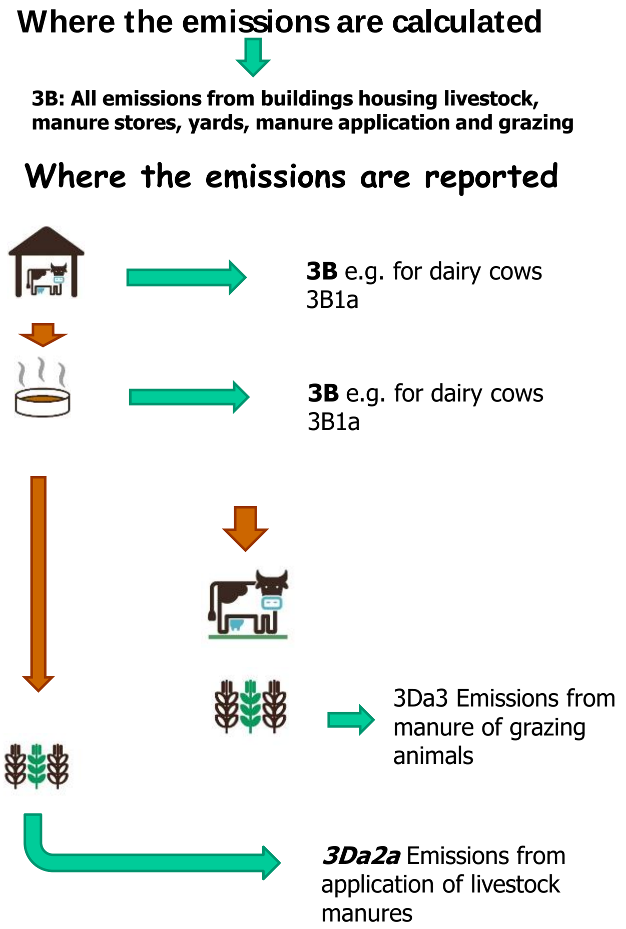
Emissions of $NH_3$ at one stage of manure management, e.g. during housing, can influence $NH_3$ emissions at later stages of manure management, e.g. during manure storage and application to land. The more $NH_3$ emitted at early stages of manure management the less is available for emission later (Reidy et al., 2007, 2009). 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. For this reason, emissions at the Tier 2 level are calculated sequentially using a mass-flow approach (Reidy et al., 2007, 2009). The Tier 1 default EFs are derived from the Tier 2 mass-flow method.

Emissions from field-applied manure and from excreta deposited by grazing animals are reported separately from those of livestock housing, outdoor yards and manure storage. This allows emissions to be reported to the current NFR reporting structure (under the United Nations Economic Commission for Europe (UNECE)), which is specifically maintained to be consistent with the common reporting format (CRF) reporting structure (under the United Nations Framework Convention on Climate Change (UNFCCC)) for greenhouse gases. Figure 3.2 illustrates which emissions are to be calculated and where they are to be reported. The full reporting requirements are given in Table 3.1.

**Table 3.1 NFR codes under which emissions from manure management are calculated and reported**

| Livestock category | Calculation | Reporting $NH_3$ emissions from | | |
|---|---|---|---|---|
| | | Housing, storage and yards | Manure application | Grazed pastures |
| Dairy cattle (dairy cows in production) | 3B1a | 3B1a | 3Da2a | 3Da3 |
| Non-dairy cattle (all other cattle) | 3B1b | 3B1b | 3Da2a | 3Da3 |
| Sheep | 3B2 | 3B2 | 3Da2a | 3Da3 |
| 'Swine' - finishing pigs | 3B3 | 3B3 | 3Da2a | 3Da3 |
| 'Swine' - sows | 3B3 | 3B3 | 3Da2a | 3Da3 |
| Buffalo | 3B4a | 3B4a | 3Da2a | 3Da3 |
| Goats | 3B4d | 3B4d | 3Da2a | 3Da3 |
| Horses | 3B4e | 3B4e | 3Da2a | 3Da3 |
| Mules and asses | 3B4f | 3B4f | 3Da2a | 3Da3 |
| Laying hens | 3B4gi | 3B4gi | 3Da2a | 3Da3 |
| Broilers | 3B4gii | 3B4gii | 3Da2a | 3Da3 |
| Turkeys | 3B4giii | 3B4giii | 3Da2a | 3Da3 |
| Other poultry | 3B4giv | 3B4giv | 3Da2a | 3Da3 |
| Other animals | 3B4h | 3B4h | 3Da2a | 3Da3 |

**Figure 3.2 Reporting procedure for source category 3B Manure management**



This explanation of the separation of calculating and reporting emissions is also relevant to NO, as this emission is also calculated using a mass-flow approach.

## 3.3 Tier 1 default approach

### 3.3.1 Algorithm

The objective of **Step 1** is to define appropriate livestock categories and obtain the annual average number of animals in each category (see subsection, 'activity data'). The aim of this categorisation is to group types of livestock that are managed similarly (typical examples are shown in Table 3.1).

The objective of **Step 2** is to decide for each cattle or pig livestock category whether manure is typically handled as slurry or solid.

The objective of **Step 3** is to find the default EF for each livestock category from subsection 3.3.2 of the present chapter.

The objective of **Step 4** is to calculate the pollutant emissions ($E_{pollutant\_animal}$) for each livestock category, using the corresponding annual average population for each category ($AAP_{animal}$) and the relevant EF ($EF_{pollutant\_animal}$):

$$E_{pollutant\_animal} = AAP_{animal} \times EF_{pollutant\_animal} \quad (1)$$

where $AAP_{animal}$ is the number of animals of a particular category that are present, on average, within the year (for a fuller explanation, see IPCC, 2006, section 10.2).

***Ammonia***

The Tier 1 method entails multiplying the AAP in each livestock category by default EFs, expressed as kg $AAP^{-1}$ $a^{-1}$ $NH_3$. There is one EF for emissions from livestock housing together with emissions from open yards and manure stores, one for emissions during grazing for ruminant livestock and one for emissions after application of manures for each livestock category. This means that when using the Tier 1 methodology for a livestock category, $NH_3$ emissions can be reported under NFR 3B for emissions from livestock housing, open yards and manure stores, while emissions from grazing and manure application can be reported for the livestock category under NFR 3D.a.3.

***Nitric oxide***

Emissions of NO-N and $N_2O$-N need to be estimated using the Tier 2 mass-flow approach to calculate $NH_3$ emissions, in order to accurately calculate the flow of TAN. The output from these calculations, as cited below, provides EFs for NO. The default Tier 1 EFs for NO have been calculated using the Tier 2 default NO-N EFs for manure storage, based on default activity data on N excretion, the proportions of TAN in excreta and, if appropriate, the length of the grazing period. If appropriate, separate EFs are provided for slurry- and litter-based manure management systems. The user may choose the EF for the predominant manure management system for that livestock category in the relevant country. These EFs have been calculated on the basis that all manure is stored before surface application without rapid incorporation. For these reasons, countries are encouraged to calculate emissions using at least a Tier 2 approach if possible.

***NMVOCs***

The Tier 1 method entails multiplying the AAP in each livestock category by a single default EF, expressed as kg NMVOC $AAP^{-1}$ $a^{-1}$. This EF represents emissions from housing. This means that when using the Tier 1 methodology for a livestock category, emissions should be reported under NFR 3B alone, and no emissions from grazing should be reported for the livestock category under NFR 3D.a.3.

Emissions from livestock on grass are assumed to be small and are only estimated as part of the Tier 2 approach.

***Particulate matter***

The Tier 1 method entails multiplying the AAP in each livestock category by a single default EF, expressed as kg PM $AAP^{-1}$ $a^{-1}$. This EF and the available methodology represent emissions from housing only, because of a lack of available information on emissions from other sources.

### *3.3.2 Default Tier 1 emission factors*

The default EFs are listed in Table 3.2 and are categorised according to pollutant and then source. Users wishing to see the same EFs categorised according to source and then pollutant are directed to annex A1.3.1.

***Ammonia***

The default Tier 1 EFs for $NH_3$ have been calculated using the Tier 2 default $NH_3$-N EFs for each stage of manure management (see section 3.4) and default activity data on N excretion, the proportions of TAN in excreta and, if appropriate, the length of the grazing period. If appropriate, separate EFs are provided for slurry- and litter-based manure management systems. The user may choose the EF for the predominant manure management system for that livestock category in the relevant country. These EFs have been calculated on the basis that all manure is stored before surface application without rapid incorporation. For these reasons, countries are encouraged to calculate emissions using at least a Tier 2 approach if possible.

**Table 3.2 Default Tier 1 EF ($EF_{NH3}$) for calculation of $NH_3$ emissions from manure management. Figures are annually averaged emissions in kg $AAP^{-1}$ $a^{-1}$ $NH_3$, as defined in subsection 3.3.1**

| Revised NFR | Livestock | Manure type | Total $EF_{NH3}$ (kg $a^{-1}$ $AAP^{-1}$ $NH_3$) | $EF_{NH3}$ (kg $a^{-1}$ $AAP^{-1}$ $NH_3$) for emissions from housing, storage and yards | $EF_{NH3}$ (kg $a^{-1}$ $AAP^{-1}$ $NH_3$) for emissions following manure application | $EF_{NH3}$ (kg $a^{-1}$ $AAP^{-1}$ $NH_3$) for emissions from grazed pastures |
|---|---|---|---|---|---|---|
| | | | | | **Reported under** | |
| | | | | **'Manure management'** | **'Manure applied to soils' (3Da2)** | **'Excreta deposited by grazing livestock' (3.D.a.3)** |
| 3B1a | Dairy cattle | Slurry | **41.8** | **22.0** | **15.4** | **4.4** |
| 3B1a | Dairy cattle | Solid | **26.4** | **16.1** | **6.0** | **4.4** |
| 3B1b | Other cattle (all other cattle) | Slurry | **15.0** | **7.9** | **5.1** | **2.0** |
| 3B1b | Other cattle | Solid | **10.0** | **5.7** | **2.2** | **2.0** |
| 3B2 | Sheep | Solid | 1.4 | 0.4 | 0.2 | 0.8 |
| 3B3 | 'Swine' - finishing pigs | Slurry | **6.5** | **3.7** | **2.8** | **0.0** |
| 3B3 | 'Swine' - finishing pigs | Solid | **5.6** | **4.2** | **1.4** | **0.0** |
| 3B3 | 'Swine' - sows | Slurry | **17.7** | **12.5** | **5.2** | **0.0** |
| 3B3 | 'Swine' - sows | Solid | **15.1** | **12.1** | **3.1** | **0.0** |
| 3B3 | 'Swine' - sows | Outdoor | **9.3** | **0.0** | **0.0** | **9.3** |
| 3B4a | Buffalo | Solid | 9.2 | 4.3 | 0.9 | 4.0 |
| 3B4d | Goats | Solid | 1.4 | 0.4 | 0.2 | 0.8 |
| 3B4e | Horses | Solid | 15.8 | 7.0 | 2.7 | 6.1 |
| 3B4f | Mules and asses | Solid | 15.8 | 7.0 | 2.7 | 6.1 |
| 3B4gi | Laying hens (laying hens and parents) | Solid | **0.31** | **0.16** | **0.15** | **0.0** |
| 3B4gi | Laying hens (laying hens and parents) | Slurry | 0.48 | 0.32 | 0.15 | 0.0 |
| 3B4gii | Broilers (broilers and parents) | Litter | **0.17** | **0.13** | **0.04** | **0.0** |
| 3B4giii | Turkeys | Litter | 0.90 | 0.56 | 0.34 | 0.0 |
| 3B4giv | Other poultry (ducks) | Litter | 0.65 | 0.45 | 0.20 | 0.0 |
| 3B4giv | Other poultry (geese) | Litter | 0.35 | 0.30 | 0.05 | 0.0 |
| 3B4h | Other livestock (fur animals) | | 0.03 | 0.02 | 0.01 | 0.0 |
| 3B4h | Other livestock (camels) | Solid | 10.5 | | | |

**Source**: IPCC, 2006; default grazing periods for cattle were taken from Table 10A 4–8, Chapter 10, 'Emissions from livestock and manure management', and default N excretion data for western Europe were taken from Table 10.19, Chapter 10 (these data are also given in Table 3.9, together with the housing period on which these EFs are based). In cases where total emissions do not add up to the sum of the components, this is due to rounding of the numbers.

'Sheep' are defined here as 'mature ewes with lambs until weaning'. To calculate emissions for lambs from weaning until slaughter, or other sheep, the EFs quoted in Table 3.2 can be adjusted according to the ratio of annual N excretion by other sheep to that of the mature ewes. Note that estimates of the number of sheep will vary according to the time of the agricultural census. If taken in summer, the count will be of ewes, rams, other sheep and finishing lambs. If taken in winter, few, if any, finishing lambs will be recorded. The 3B sub-category 'sows' includes piglets up to 8 kg. Pigs of 8 kg and above are included in the 3B sub-category 'finishing pigs'. Details of how the activity data should be calculated are given in subsection on activity data. The default EFs presented in Table 3.2 were calculated using the Tier 2 approach outlined in subsection 3.4 using default EFs for each emission derived using the approaches described in annex A1.3.2.

***Nitric oxide***

NO emissions are reported together with $NO_2$ emissions, as NOx. Therefore NO emissions must be converted to $NO_2$ when reporting emissions of NOx. To enable direct reporting by GB users RFs for NO are shown in Table 3.3 as kg $a^{-1}$ $NO_2$.

**Table 3.3 Default Tier 1 EFs for NO (as $NO_2$) from stored manure. According to Annex I of the NFR Reporting Guidelines, NO emissions have to be reported as $NO_2$, hence the EFs below are provided as $NO_2$**

| NFR | Livestock | Manure type | $EF_{NO}$ (kg $a^{-1}$ $AAP^{-1}$ $NO_2$) |
|---|---|---|---|
| 3B1a | Dairy cattle | Slurry | 0.010 |
| 3B1a | Dairy cattle | Solid | 0.752 |
| 3B1b | Non-dairy cattle (all other cattle) | Slurry | 0.003 |
| 3B1b | Non-dairy cattle | Solid | 0.217 |
| 3B2 | Sheep | Solid | 0.012 |
| 3B3 | 'Swine' – finishing pigs* | Slurry | 0.002 |
| 3B3 | 'Swine' – finishing pigs* | Solid | 0.017 |
| 3B3 | 'Swine' – sows | Slurry | 0.005 |
| 3B3 | 'Swine' – sows | Solid | 0. 471 |
| 3B3 | 'Swine' – sows | Outdoor | 0 |
| 3B4a | Buffalo | Solid | 0.083 |
| 3B4d | Goats | Solid | 0.012 |
| 3B4e | Horses | Solid | 0.250 |
| 3B4f | Mules and asses | Solid | 0.250 |
| 3B4gi | Laying hens (laying hens and parents) | Solid | 0.014 |
| 3B4gi | Laying hens (laying hens and parents) | Slurry | 0.0001 |
| 3B4gii | Broilers (broilers and parents) | Litter | 0.027 |
| 3B4giii | Turkeys | Litter | 0.027 |
| 3B4giv | Other poultry (ducks) | Litter | 0.022 |
| 3B4giv | Other poultry (geese) | Litter | 0.005 |
| 3B4h | Other animals | Litter | 0.001 |

**Source**: IPCC, 2006; default grazing periods for cattle were taken from Table 10A 4–8, Chapter 10, 'Emissions from livestock and manure management', and default N excretion data for western Europe were taken from Table 10.19, Chapter 10 (these data are also given in Table 3.9, together with the housing period on which these EFs are based). * Pigs of 8 kg until slaughter weight.

***Non-methane volatile organic compounds***

The default Tier 1 NMVOC EFs in Table 3.4 are based on results from a study (the National Air Emissions Monitoring (NAEM) study) in the USA (US EPA, 2012). This NAEM study included NMVOC measurements from 16 different livestock production facilities covering dairy cattle, sows, finishers, egg layers and broilers. The average measured emissions were converted to agricultural conditions for western Europe by using Intergovernmental Panel on Climate Change (IPCC) default values for livestock feed intake and excretion of volatile substances (VS) (US EPA, 2012; IPCC 2006; Shaw et al., 2007). The EFs for other cattle, sheep, goats, horses, mules and asses, rabbits, reindeer, camels and buffaloes are based on the values for the relative VS excretion rates from the IPCC 2006 guidelines. Please refer to annex 1, section A1.2.3, for a detailed explanation.

Silage is a major source of emissions; therefore, there is a need to distinguish between feed intake with and without silage. No distinction has been made between liquid and solid manure as the limited data do not allow such a differentiation. The assumed lengths of the housing periods are shown in Table 3.9.

Countries are encouraged to calculate emissions using a Tier 2 approach if possible.

**Table 3.4 Default Tier 1 EFs for NMVOCs**

| Code | Livestock | EF, with silage feeding | EF, without silage feeding |
|---|---|---|---|
| | | NMVOC, kg AAP$^{-1}$ a$^{-1}$ | |
| 3B1a | Dairy cattle | 17.937 | 8.047 |
| 3B1b | Non-dairy cattle ($^{a}$) | 8.902 | 3.602 |
| 3B2 | Sheep | 0.279 | 0.169 |
| 3B3 | 'Swine' (finishing pigs ($^{b}$)) | – | 0.551 |
| 3B3 | 'Swine (sows) | – | 1.704 |
| 3B4a | Buffalo | 9.247 | 4.253 |
| 3B4d | Goats | 0.624 | 0.542 |
| 3B4e | Horses | 7.781 | 4.275 |
| 3B4f | Mules and asses | 3.018 | 1.470 |
| 3B4gi | Laying hens (laying hens and parents) | – | 0.165 |
| 3B4gii | Broilers (broilers and parents) | – | 0.108 |
| 3B4giii | Turkeys$^{3}$ | – | 0.489 |
| 3B4giv | Other poultry (ducks, geese) ($^{c}$) | – | 0.489 |
| 3B4h | Other animals (fur animals) ($^{d}$) | – | 1.941 |
| 3B4h | Other animals (rabbits) | – | 0.059 |
| 3B4h | Other animals (reindeer ($^{e}$)) | – | 0.045 |
| 3B4h | Other animals (camels) | – | 0.271 |

($^{a}$) Includes all other cattle.

($^{b}$) Includes pigs from 8 kg to slaughtering.

($^{c}$) Based on data for turkeys.

($^{d}$) A 'fur animal' is any animal raised and slaughtered only for its fur.

($^{e}$) Assumes 100 % grazing.

***Particulate matter***

Emissions of PM occur from both housed and free-range or grazing livestock. However, emission measurements have focused on housed livestock, and a general lack of available information in the scientific literature means that EFs that are specific to free-range or grazing livestock are not available. The processes that give rise to emissions from housed poultry are similar to those for free-range poultry. So, when calculating PM emissions using the Tier 1 default EFs, it is good practice to use the housed livestock EFs for estimating emissions from both housed and free-range poultry. For other livestock types, grazing animals are not considered to be subject to the same processes for PM emissions as those within livestock housing. So it is good practice to apply the Tier 1 EFs to housed livestock only. Knowledge of a variety of different parameters is important in order to determine emissions of PM, of which the most decisive parameters are feeding conditions, animal activity and bedding material. The $PM_{10}$ and $PM_{2.5}$ EFs are based on the most up-to-date literature. Takai et al. (1998) and Winkel et al. (2015) and the overviews of publications presented therein are the main sources for the EFs. Recently undertaken studies present smaller EFs than those derived from Takai et al. (1998); therefore, around 50 % of the EFs have been updated. This decrease could be explained by changes in livestock management practices. The footnote of Table 3.5 provides a complete list of the studies considered and annex 1 provides a detailed description.

**Table 3.5 Default Tier 1 estimates of EF for particle emissions from livestock husbandry (housing)**

| Code | Livestock | EF for TSP (kg AAP$^{-1}$ a$^{-1}$) | EF for PM$_{10}$ (kg AAP$^{-1}$ a$^{-1}$) | EF for PM$_{2.5}$ (kg AAP$^{-1}$ a$^{-1}$) |
|---|---|---|---|---|
| 3B1a | Dairy cattle | 1.38 (a) | 0.63 (a) | 0.41 (a) |
| 3B1b | Non-dairy cattle (all other cattle except calves) | 0.59 (a) | 0.27 (a) | 0.18 (a) |
| 3B1b | Non-dairy cattle (calves) | 0.34 (a) | 0.16 (a) | 0.10 (a) |
| 3B2 | Sheep | 0.14 (b) | 0.06 (b) | 0.02 (b) |
| 3B3 | ‘Swine’ (finishing pigs) | 1.05(c) | 0.14 (d) | 0.006 (e) |
| 3B3 | ‘Swine’ (weaners) | 0.27 (c) | 0.05 (f) | 0.002 (c) |
| 3B3 | ‘Swine’ (sows) | 0.62 (c) | 0.17 (f) | 0.01 (c) |
| 3B4a | Buffalo | 1.45 (a) | 0.67 (a) | 0.44 (a) |
| 3B4d | Goats | 0.14 (b) | 0.06 (b) | 0.02 (b) |
| 3B4e | Horses | 0.48 (g) | 0.22 (g) | 0.14 (g) |
| 3B4f | Mules and asses | 0.34 (a) | 0.16 (a) | 0.10 (a) |
| 3B4gi | Laying hens (laying hens and parents) | 0.19 (c) | 0.04 (h) | 0.003 (i) |
| 3B4gii | Broilers (broilers and parents) | 0.04 (c) | 0.02 (j) | 0.002 (k) |
| 3B4giii | Turkeys | 0.11 (l) | 0.11 (m) | 0.02 (c) |
| 3B4giv | Other poultry (ducks) | 0.14 (a) | 0.14 (a) | 0.02 (a) |
| 3B4giv | Other poultry (geese) | 0.24 (a) | 0.24 (a) | 0.03 (a) |
| 3B4h | Other animals (fur animals) | 0.018 (b) | 0.008 (b) | 0.004 (b) |

**Notes:** The PM$_{2.5}$ EFs for pigs (‘Swine’) presented here represent the information available from the scientific literature. However, caution should be used with these EFs as the ratio between PM$_{10}$ and PM$_{2.5}$ is considerably different from that for larger livestock categories, suggesting a particularly high degree of uncertainty with these data. A 'fur animal' is any animal raised and slaughtered only for its fur.

**Sources**:

(a) Takai et al. (1998).

(b) Mosquera and Hol (2011); Mosquera et al. (2011).

(c) Winkel et al. (2015).

(d) Chardon and van der Hoek (2002); Schmidt et al. (2002) cited in Winkel et al. (2015); Jacobson et al. (2004); Koziel et al. (2004) cited in Winkel et al. (2015); Haeussermannn et al. (2006, 2008); Costa et al. (2009); Van Ransbeeck et al. (2013; Winkel et al. (2015).

(e) Van Ransbeeck et al. (2013); Winkel et al. (2015).

(f) Haeussermann et al. (2008); Costa et al. (2009); Winkel et al. (2015).

(g) Seedorf and Hartung et al. (2001).

(h) Lim et al. (2003); Demmers et al. (2010); Costa et al. (2012) cited in Winkel et al. (2015); Valli et al. (2012); Hayes et al. (2013); Shepherd et al. (2015); Winkel et al. (2015); Haeussermann et al. (2008); Costa et al. (2009); Winkel et al. (2015).

(i) Lim et al. (2003); Demmers et al. (2010); Hayes et al. (2013); Shepherd et al. (2015); Fabbri et al. (2007); Dunlop et al. (2013); Winkel et al. (2015).

(j) Redwine et al. (2002); Lacey et al. (2003); Roumeliotis and Van Heyst (2007); Calvet et al. (2009); Demmers et al. (2010); Modini et al. (2010); Roumeliotis et al. (2010); Lin et al. (2012) cited in Winkel et al. (2015); Winkel et al. (2015).

(k) Roumeliotis and Van Heyst (2007); Demmers et al. (2010); Modini et al. (2010); Roumeliotis et al. (2010); Lin et al. (2012) cited in Winkel et al. (2015); Winkel et al. (2015).

(l) Assume same ratio for TSP to PM10 as ‘Other poultry’.

(m) Schmidt et al. (2002) cited in Winkel et al. (2015); Li et al. (2008) cited in Winkel et al. (2015); Winkel et al. (2015).

(n) Lim et al. (2003); Fabbri et al. (2007); Demmers et al. (2010); Costa et al. (2012) cited in Winkel et al. (2015); Valli et al. (2012); Hayes et al. (2013); Shepherd et al. (2015); Dunlop et al. (2013); Winkel et al. (2015).

TSP, total suspended particles.

### 3.3.3 Activity data

For Tier 1, data are required on livestock numbers for each of the categories listed in Table 3.1. An annual national agricultural census can supply these data. Otherwise, statistical information from Eurostat (http://ec.europa.eu/eurostat) or the Food and Agriculture Organization of the United Nations (FAO) Statistical Yearbooks (e.g. FAO, 2014) can be used. Definitions of the terms used in the explanation of how to calculate annual emissions are provided in Table 3.6.

As mentioned above, the AAP is the average number of animals of a particular category that are present, on average, within the year. This number can be obtained by a number of methods. If the number of animals present on a particular day does not change over the year, a census of the animals present on a particular day will give the AAP. However, if the number of animals present varies over the year, e.g. because of seasonal production cycles, it may be more accurate to base the AAP on a census of the number of animal places. If this is done, allowance has to be made for the time that the animal place is empty. There can be a number of reasons why the animal place may be empty for part of the year, but the most common are that the production is seasonal or because the building is being cleaned in preparation for the next batch of animals.

**Table 3.6 Definitions of the terms used in the explanation of how to calculate annual emissions**

| Terms | Units | Definition |
|---|---|---|
| Annual average population (AAP) | – | Number of animals of a particular category that are present, on average, within the year |
| Animal places (nplaces) | – | Average capacity for a housed livestock category that is usually occupied |
| Milk yield | L $a^{-1}$ | The mean amount (L) of milk produced by the dairy cow during the year for which annual emissions are to be calculated |
| Empty period (tempty) | d | The average duration during the year when the animal place is empty (in d) |
| Cleaning period (tcleanse) | d | The time between production cycle or rounds when the animal place is empty, e.g. for cleaning (in d) |
| Production cycle (nround) | – | The average number of production cycles per year |
| Number of animals produced (nprod) | $a^{-1}$ | The number of animals produced during the year |
| Proportion dying (xns) | – | Proportion of animals that die and are not sold |

If the AAP is estimated from the number of places ($n_{places}$), the calculation is:

$$AAP = n_{places} \times (1 - t_{empty}/365) \qquad (2)$$

If the duration of an animal life or the time that animals remain within a category is less than 1 year, it will be common to have more than one production cycle per year. In this situation, $t_{empty}$ will be the product of the number of production cycles or rounds ($n_{round}$) per year and the duration per round of the period during which the animal place is empty ($t_{cleanse}$):

$$t_{empty} = n_{round} \times t_{cleanse} \qquad (3)$$

A third method of estimating AAP is to use statistics recording the number of animals produced per year:

$$AAP = n_{prod}/(n_{round} \times (1 - x_{ns})) \qquad (4)$$

where $x_{ns}$ is the proportion of animals that die and are not sold.

## 3.4 Tier 2 technology-specific approach

### *3.4.1 Algorithm for ammonia and nitric oxide*

Tier 2 uses a mass-flow approach based on the concept of a flow of TAN through the manure management system, as shown in the schematic diagram in Figure 2.2. It should be noted that the calculations of a mass-flow approach must be carried out on the basis of kg of N. The resultant estimates of $NH_3$-N emissions are then converted to $NH_3$. If calculating emissions of $NH_3$ using a mass-flow approach, a system based on TAN is preferred to one based on total N, as is used by IPCC to estimate emissions of $N_2O$. This is because emissions of $NH_3$ and other forms of gaseous N arise from TAN. Accounting for the TAN in manure as it passes through the manure management system therefore allows for more accurate estimates of gaseous N emissions. It also allows for the methodology to reflect the consequences of changes in livestock diets on gaseous N emissions, since the excretion of total N and TAN respond differently to such changes. Such estimates of the percentage of TAN in manures may be used to verify the accuracy of the mass-flow calculations (e.g. Webb and Misselbrook, 2004).

Despite the apparent complexity of this approach, the methodology is not inherently difficult to use; it does, however, necessarily require much more input data than the Tier 1 methodology. Different systems are represented at each stage to account for real differences in management systems and resulting emissions. In particular, distinctions are made between slurry and solid systems at each stage.

The adoption of a consistent N-flow model, based on proportional transfers of TAN, allows different options or pathways to be incorporated, in order to account for differences among real-world systems. This approach has several advantages over the Tier 1 methodology, as outlined below.

- The method ensures that there is consistency between the N species reported using this guidebook (e.g. under the LRTAP Convention) and those reported using the IPCC Guidelines.
- A mass balance can be used to check for errors (the N excreted plus the N added in bedding minus the N emitted, and the N entering the soil should be zero).
- The impacts of making changes at one stage of manure management (upstream) on emissions at later stages of manure management (downstream) can be taken into account, e.g. differences in emissions during housing will, by leading to different amounts of TAN entering storage and field application, give rise to differences in the potential size of $NH_3$ emissions during storage or after field application.

The greatest potential benefit arises when the mass-flow approach is further developed to a Tier 3 methodology that can make proper allowances for the introduction of abatement techniques.

- Possible abatement measures can be also included as alternative systems. This approach ensures that the changes in the N-flow through the different sources that occur as a result of the use of abatement measures are correct. This makes it easier to document the effect of abatement (reduction) measures that have already been introduced or are considered for the future. Hence, this Tier 2 approach may be considered a step towards developing a Tier 3 methodology (see section 3.5 below).

Default values are provided for N excretion, the proportion of TAN and the emissions at each stage of manure management (Table 3.9). It is good practice for every country to use country-specific activity data. Table A1.10 explains how the default $NH_3$-N EF was derived, which may be helpful for calculating country-specific EFs for Tier 3. Country-specific EFs may give rise to more accurate estimates of emissions because they encompass a unique combination of activities within that country or because they have different estimates of emissions from a particular activity within the country, or both. The amount of N flowing through the different pathways may be determined by country-specific information on livestock husbandry and manure management systems, while the proportion volatilised as $NH_3$-N at each stage in the system is treated as a percentage, based primarily on measured values and, if necessary, expert judgement.

Tier 2 methodologies estimate the mineralisation of N and the immobilisation of TAN during manure management, and also estimate other losses of N, e.g. as NO, in order to more accurately estimate the TAN available at each stage of manure management.

In the stepwise procedure outlined below, manure is assumed to be managed as either slurry or solid. Slurry consists of excreta, spilt livestock feed and drinking water, some bedding material and water added during cleaning or to assist in handling. It is equivalent to the liquid/slurry category described in IPCC (2006). For more information, see Table 3.13 (section 3.4.5), which relates storage categories commonly referred to in $NH_3$ inventories to the classification used by the IPCC. Solid manure consists of excreta, spilt livestock feed and drinking water, and may also include bedding material. It is equivalent to the solid manure category described in IPCC, 2006. For situations in which manure is separated into liquid and solid fractions, the liquid should be treated as slurry.

The objective of **Step 1** is to define the livestock subcategories that are homogeneous with respect to feeding, excretion and age/weight range. Typical livestock categories are shown in Table 3.1. The corresponding number of animals has to be obtained, as described in subsection 3.4.1. Steps 2 to 14 inclusive should then be applied to each of these subcategories and the emissions summed.

In **Step 2**, the total annual excretion of N by the animals **(**$N_{ex}$; kg $AAP^{-1}$ $a^{-1}$) is calculated. Many countries have detailed procedures to derive N excretion rates for different livestock categories. If these are not available, the method described in chapter 10 of IPCC, 2006 (equations 10.31, 10.32 and 10.33) should be used as guidance, where $N_{ex}$ is equivalent to $Nex_{(T)}$. For convenience, default values are given in

Table 3.9; these are derived from the estimates of N excretion used to calculate national $NH_3$ emissions by the EAGER network.

The purpose of **Step 3** is to calculate the amount of the annual N excreted that is deposited within buildings in which livestock are housed, on uncovered yards and during grazing. This is based on the total annual N excretion ($N_{ex}$) and the proportions of excreta deposited at these locations ($x_{hous}$, $x_{yards}$ and $x_{graz}$, respectively). These proportions depend on the fraction of the year that animals spend in buildings, on yards and grazing, and on animal behaviour. In this document EFs for the calculation of emissions from outdoor yard areas are only provided for the categories 3B1a, 3B1b and 3B2. The proportions of N excreta deposited on these yard areas are taken to be: 3B1a, 0.25; 3B1b, 0.10; 3B2, 0.02 of annual N excretion. In some countries any type of livestock may be held on concreted areas that are only partially roofed or have no roof at all. To calculate yard emissions for livestock for which no EFs are currently available the user should take the EF and the proportion of excreta deposited on the hard standing from the most similar category for which data are available. Unless better information is available, $x_{hous}$, $x_{yards}$ and $x_{graz}$ should equate to the proportion of the year spent at the relevant location, and must always add up to 1.0.

$$m_{graz\_N} = x_{graz} \times N_{ex} \tag{5}$$

$$m_{yard\_N} = x_{yards} \times N_{ex} \tag{6}$$

$$m_{hous\_N} = x_{hous} \times N_{ex} \tag{7}$$

In **Step 4** the proportion of the N excreted as TAN ($x_{TAN}$) is used to calculate the amount of TAN deposited during grazing, on yards or during housing ($m_{graz\_TAN}$, $m_{yard\_TAN}$ and $m_{hous\_TAN}$).

$$m_{graz\_TAN} = x_{TAN} \times m_{graz\_N} \tag{8}$$

$$m_{yard\_TAN} = x_{TAN} \times m_{yard\_N} \tag{9}$$

$$m_{hous\_TAN} = x_{TAN} \times m_{hous\_N} \tag{10}$$

If detailed national procedures for deriving N excretion rates that provide the proportion of N excreted as TAN are available, these should be used. If these are not available, the default values shown in Table 3.9 should be used.

The objective of **Step 5** is to calculate the amounts of TAN and total N deposited during housing handled as liquid slurry ($m_{hous\_slurry\_TAN}$) or as solid ($m_{hous\_solid\_TAN}$).

$$m_{hous\_slurry\_TAN} = x_{slurry} \times m_{hous\_TAN} \tag{11}$$

$$m_{hous\_slurry\_N} = x_{slurry} \times m_{hous\_N} \tag{12}$$

$$m_{hous\_solid\_TAN} = (1 - x_{slurry}) \times m_{hous\_TAN} \tag{13}$$

$$m_{hous\_solid\_N} = (1 - x_{slurry}) \times m_{hous\_N} \tag{14}$$

where $x_{slurry}$ is the proportion of livestock manure handled as slurry (the remainder is the proportion of livestock manure handled as solid).

In **Step 6**, the $NH_3$-N losses and $E_{hous}$, from the livestock housing and from the yards, are calculated by multiplying the amount of TAN ($m_{hous\_TAN}$) by $EF_{hous}$ ($NH_3$-N), for both slurry and solid manure (including FYM):

$$E_{hous\_slurry} = m_{hous\_slurry\_TAN} \times EF_{hous\_slurry} \tag{15}$$

$$E_{hous\_solid} = m_{hous\_solid\_TAN} \times EF_{hous\_solid} \tag{16}$$

And by multiplying the amount of TAN ($m_{yard,TAN}$) by $EF_{yard}$:

$$E_{yard} = m_{yard,TAN} \times EF_{yard} \qquad (17)$$

This will give emissions as kg $NH_3$-N.

**Step 7** applies to only solid manure. Its function is to allow for the addition of N in animal bedding ($m_{bedding}$) in these litter-based housing systems and to account for the consequent immobilisation of TAN in that bedding. The amounts of total-N and TAN in solid manure that are removed from livestock housing and yards ($m_{ex\text{-}hous\_solid\_N}$ and $m_{ex\text{-}hous\_solid\_TAN}$), and either passed to storage or applied directly to the fields, are then calculated, remembering to subtract the $NH_3$-N emissions during livestock housing.

If detailed information is lacking, the amounts of straw used and the N inputs ($m_{bedding\_N}$) can be obtained from the example calculation spreadsheet available from the same location as the online version of this guidebook (see Table 3.7).

**Table 3.7 Default values for length of housing period, annual straw use in litter-based manure management systems and the N content of straw**

| Livestock category | Housing period, day | Straw, kg AAP$^{-1}$ a$^{-1}$ | ([a]) N added in straw, kg AAP$^{-1}$ a$^{-1}$ |
|---|---|---|---|
| Dairy cattle (3B1a) | 180 | 1,500 | 6.00 |
| Non-dairy cattle (3B1b) | 180 | 500 | 2.00 |
| Finishing pigs (3B3) | 365 | 200 | 0.80 |
| Sows (3B3) | 365 | 600 | 2.40 |
| Sheep and goats (3B2 and 3B4d) | 30 | 20 | 0.08 |
| Horses, etc. (3B4e and 3B4f) | 180 | 500 | 2.00 |
| Buffalos (3B4a) | 225 | 1,500 | 6.00 |

([a]) Based on a straw N content of 4 g kg$^{-1}$.

The amounts of straw given are for the stated housing period. For longer or shorter housing periods, the straw used may be adjusted in proportion to the length of the housing period.

Account must also be taken of the fraction of TAN that is immobilised in organic matter ($f_{imm}$) when manure is managed as a litter-based solid and the litter is straw, as this immobilisation will greatly reduce the potential $NH_3$-N emission during storage and after application (including from manures applied directly from livestock housing).

$$m_{ex\text{-}hous\_solid\_TAN} = m_{hous\_solid\_TAN} - (E_{hous\_solid} + (m_{bedding} \times f_{imm})) \quad (18)$$

$$m_{ex\text{-}hous\_solid\_N} = m_{hous\_solid\_N} + m_{bedding\_N} - E_{hous\_solid} \quad (19)$$

where $m_{bedding}$ is the mass of bedding (kg fresh weight a$^{-1}$) and $m_{bedding\_N}$ is the mass of nitrogen in that bedding (= approximately $m_{bedding}/100$).

If data for $f_{imm}$ are not available, it is recommended that a $f_{imm}$ value of 0.0067 kg N kg$^{-1}$ straw is used (Webb and Misselbrook, 2004, based on data reported by Kirchmann and Witter, 1989). Default values for the mass of bedding are given in Table 3.7. No values are given for poultry as manure is generally kept dry and immobilisation is unlikely to take place.

The objective of **Step 8** is to calculate the amounts of total-N and TAN stored before application to land. Not all manures are stored before application; some will be applied to fields directly from livestock housing. Some manures (mainly slurries) will be used as feedstocks for AD in biogas facilities ($x_{biogas\_slurry}$ and $x_{biogas\_solid}$). Emissions from biogas facilities i.e. from during the storage of slurry before anaerobic digestion and the storage of digestate after biogas generation, are calculated and reported in Chapter 5B2. Hence, any manures used as biogas feedstocks need to be subtracted before calculating emissions from storage and application to land. Therefore, the proportions of slurry and solid manure stored on farms ($x_{store\_slurry}$ and $x_{store\_solid}$), together with $x_{biogas\_slurry}$ and $x_{biogas\_solid}$, must be known.

***For slurry***:

$$m_{storage\_slurry\_TAN} = [(m_{hous\_slurry\_TAN} - E_{hous\_slurry}) + (m_{yard\_TAN} - E_{yard})] \times x_{store\_slurry} \quad (20)$$

$$m_{storage\_slurry\_N} = [(m_{hous\_slurry\_N} - E_{hous\_slurry}) + (m_{yard\_N} - E_{yard})] \times x_{store\_slurry} \quad (21)$$

$$m_{biogas\_slurry\_TAN} = [(m_{hous\_slurry\_TAN} - E_{hous\_slurry}) + (m_{yard\_TAN} - E_{yard})] \times x_{biogas\_slurry} \quad (22)$$

$$m_{biogas\_slurry\_N} = [(m_{hous\_slurry\_N} - E_{hous\_slurry}) + (m_{yard\_N} - E_{yard})] \times x_{biogas\_slurry} \quad (23)$$

$$m_{applied\_direct\_slurry\_TAN} = [(m_{hous\_slurry\_TAN} - E_{hous\_slurry}) + (m_{yard\_TAN} - E_{yard})] \times (1 - (x_{store\_slurry} + x_{biogas\_slurry})) \quad (24)$$

$$m_{applied\_direct\_slurry\_N} = [(m_{hous\_slurry\_N} - E_{hous\_slurry}) + (m_{yard\_N} - E_{yard})] \times (1 - (x_{store\_slurry} + x_{biogas\_slurry})) \quad (25)$$

To ensure that all of the slurry is accounted for, and that there is no duplication, the sum of the proportions of $x_{store\_slurry}$ and $x_{biogas\_slurry}$ and the proportion of slurry applied directly to land without storage or digestion must amount to 1.0.

***For solid***:

$$m_{storage\_solid\_TAN} = m_{ex\text{-}hous\_solid\_TAN} \times x_{store\_solid} \quad (26)$$

$$m_{storage\_solid\_N} = m_{ex\text{-}hous\_solid\_N} \times x_{store\_solid} \quad (27)$$

$$m_{biogas\_solid\_TAN} = m_{ex\text{-}hous\_solid\_TAN} \times x_{biogas\_solid} \quad (28)$$

$$m_{biogas\_solid\_N} = m_{ex\text{-}hous\_solid\_N} \times x_{biogas\_solid} \quad (29)$$

$$m_{appl\_direct\_solid\_TAN} = m_{ex\text{-}hous\_solid\_TAN} \times (1 - (x_{store\_solid} + x_{biogas\_solid})) \quad (30)$$

$$m_{appl\_direct\_solid\_N} = m_{ex\text{-}hous\_solid\_N} \times (1 - (x_{store\_solid} + x_{biogas\_solid})) \quad (31)$$

As for slurry, and if there is no duplication, the sum of the proportions $x_{store\_solid}$ and $x_{biogas\_solid}$ and the proportion of slurry applied directly to land without storage or digestion must amount to 1.0.

The equations provided for Step 8 assume that the N and TAN remaining on yards after $NH_3$ emission are collected and either put into the slurry store, applied directly on to land or used as AD feedstock (Equations 20–23). In some countries where the weather is typically warm and dry, the excreta deposited on yards may dry before the yards are cleaned and the scrapings are applied to a solid manure store. In such cases, Equations 20–27 should be adjusted to place the N and TAN remaining on yards after $NH_3$ emission into the solid store.

The masses of TAN and total N ($m_{biogas\_slurry\_TAN}$ and $m_{biogas\_slurry\_N}$) are used in the Tier 2 methodology for calculating $NH_3$ emission from anaerobic digestion facilities (biogas production) in chapter 5.B.2..

**Step 9** applies to only slurries and its function is to calculate the amount of TAN from which emissions will occur from slurry stores. For slurries, a fraction of the organic N is mineralised ($f_{min}$) to TAN before the gaseous emissions are calculated.

The modified mass $mm_{storage,slurry,TAN}$, from which emissions are calculated, is calculated as in Equation 28:

$$mm_{storage\_slurry\_TAN} = m_{storage\_slurry\_TAN} + ((m_{storage\_slurry\_N} - m_{storage\_slurry\_TAN}) \times f_{min}) \quad (32)$$

If data for $f_{min}$ are not available, it is recommended that an $f_{min}$ value of 0.1 is used (Dämmgen et al., 2007).

In **Step 10**, the emissions of $NH_3$-N, $N_2O$-N, NO-N and $N_2$ are calculated (using the corresponding EFs $EF_{storage}$ and $mm_{storage\_TAN}$).

***For slurry***:

$$E_{storage\_slurry} = E_{storage\_slurry\_NH3} + E_{storage\_slurry\_N2O} + E_{storage\_slurry\_NO} + E_{storage\_slurry\_N2}$$

$$= mm_{storage\_slurry\_TAN} \times (EF_{storage\_slurry\_NH3} + EF_{storage\_slurry\_N2O} + EF_{storage\_slurry\_NO} + EF_{storage\_slurry\_N2}) \quad (33)$$

***For solid manure emissions***:

$$E_{storage\_solid} = E_{storage\_solid\_NH3} + E_{storage\_solid\_N2O} + E_{storage\_solid\_NO} + E_{storage\_solid\_N2} = m_{storage\_solid\_TAN} \times ( EF_{storage\_solid\_NH3} + EF_{storage\_solid\_N2O} + EF_{storage\_solid\_NO} + EF_{storage\_ solid\_N2}) \quad (34)$$

For both slurry and litter-based manures, default values for the EFs are given in Table 3.8 ($N_2O$-N), Table 3.9 ($NH_3$-N) and Table 3.10 (NO-N and $N_2$-N). Equations 28 and 29 provide the Tier 2 EF for NO-N.

**Table 3.8 Default Tier 2 EFs for direct $N_2O$-N emissions from manure management. Table 3.13 explains how the manure storage types referred to here relate to those used by the IPCC. Table A1.7 shows how the default EFs presented below were derived.**

| Storage system | EF kg $N_2O$-N (kg TAN entering store)$^{-1}$ |
|---|---|
| Cattle slurry without natural crust | 0 |
| Cattle slurry with natural crust | 0.01 |
| Pig slurry without natural crust | 0 |
| Cattle manure heaps, solid | 0.02 |
| Pig manure heaps, solid | 0.01 |
| Sheep and goat manure heaps, solid | 0.02 |
| Horse (mules and asses) manure heaps, solid | 0.02 |
| Layer manure heaps, solid | 0.002 |
| Broiler manure heaps, solid | 0.002 |
| Turkey and duck manure heaps, solid | 0.002 |
| Goose manure heaps, solid | 0.002 |
| Buffalo manure heaps, solid | 0.02 |

The derivation of these EFs as a proportion of TAN is given in Annex 1, Table A1.7.

In **Step 11**, the total-N and TAN ($m_{applic\_N}$ and $m_{applic\_TAN}$) that is applied to the field is then calculated, remembering to subtract the emissions of $NH_3$, $N_2O$, NO and $N_2$ from storage, and add the digestate created by the anaerobic digestion of manure, that is returned from chapter 5.B.2.

***For slurry and digestate***:

$$m_{applic\_slurry\_TAN} = m_{appl\_direct\_slurry\_TAN} + mm_{storage\_slurry\_TAN} + mm_{dig\_TAN} - E_{storage\_slurry} \quad (35)$$

$$m_{applic\_slurry\_N} = m_{appl\_direct\_slurry\_N} + mm_{storage\_slurry\_N} + mm_{dig\_N} - E_{storage\_slurry} \quad (36)$$

$mm_{dig\_TAN}$ and $mm_{dig\_N}$ are calculated in equations 6 and 7 in chapter 5.B.2. Note that digestate will be a liquid and therefore any digestate arising from solid manures will be included in equations 35 and 36 above.

***For solid***:

$$m_{applic\_solid\_TAN} = m_{appl\_direct\_solid\_TAN} + mm_{storage\_solid\_TAN} - E_{storage\_solid\_TAN} \quad (37)$$

$$m_{applic\_solid\_N} = m_{appl\_direct\_solid\_N} + mm_{storage\_solid\_N} - E_{storage\_slurry\_solid\_N} \quad (38)$$

In **Step 12**, the emission of $NH_3$-N during and immediately after field application is calculated using $EF_{applic}$ (Table 3.9) combined with $m_{applic\_TAN}$.

***For slurry***:

$$E_{applic\_slurry} = m_{applic\_slurry\_TAN} \times EF_{applic\_slurry} \quad (39)$$

***For solid***:

$$E_{applic\_solid} = m_{applic\_solid\_TAN} \times EF_{applic\_solid} \quad (40)$$

In **Step 13**, the net amount of N returned to soil from manure ($m_{returned\_N}$ and $m_{returned\_TAN}$) after losses of $NH_3$-N is calculated.

***For slurry***:

$$m_{returned\_slurry\_TAN} = m_{applic\_slurry\_TAN} - E_{applic\_slurry} \quad (41)$$

$$m_{returned\_slurry\_N} = m_{applic\_slurry\_N} - E_{applic\_slurry} \quad (42)$$

***For solid***:

$$m_{returned\_solid\_TAN} = m_{applic\_solid\_TAN} - E_{applic\_solid} \quad (43)$$

$$m_{returned\_solid\_N} = m_{applic\_solid\_N} - E_{applic\_solid} \quad (44)$$

Note that the gross amount of N returned to soil during grazing ($m_{graz\_N}$), before the loss of $NH_3$-N (to be used in the calculation of subsequent emissions of NO in Chapter 3.D, 'Crop production and agricultural soils'), was calculated in Equation 5.

In **Step 14**, the $NH_3$-N emissions from grazing are calculated:

$$E_{graz} = m_{graz\_TAN} \times EF_{grazing} \quad (45)$$

No distinction is made between emissions from cattle and sheep excreta.

In **Step 15**, all the emissions from the manure management system that are to be reported under Chapter 3B are summed and converted to the mass of the relevant compound:

$$E_{MMS\_NH3} = (E_{yard\_NH3} + E_{house\_slurry} + E_{house\_solid} + E_{storage\_NH3\_slurry} + E_{storage\_NH3\_solid}) \times 17/14 \quad (46)$$

According to Annex I of the NFR Reporting Guidelines, NO emissions have to be reported as $NO_2$.

$$E_{MMS\_NO2} = (E_{storage\_NO\_slurry} + E_{storage\_NO\_solid}) \times 46/14 \quad (47)$$

where $E_{MMS\_NH3}$ and $E_{MMS\_NO2}$ are the emissions from the manure management system of $NH_3$ and $NO_2$, respectively (in kg).

The NO emissions from manure, digestate or excreta deposited during grazing is calculated in Chapter 3.D, Crop production and agricultural soils. For the calculation of these emissions, the N applied in manure that should be used in equation 1 in Chapter 3D is the sum of $m_{applic\_slurry\_N}$, $m_{applic\_solid\_N}$ and $m_{graz\_N}$.

As a quality control, the N balance should be calculated, i.e. the total input of N (total amount of N in animal excretion plus the total amount in bedding) should match the output of N (total of all emissions, N inputs to the soil and N in manures used as AD feedstocks). However, in order to check the mass balance calculations, the net return of N during grazing needs to be calculated as well, using the equivalent equation to that used to calculate net returns after manure application.

### *3.4.2 Algorithm for non-methane volatile organic compounds*

NMVOC emissions arise from six different sources:

1. silage stores
2. the feeding table if silage is used for feeding
3. livestock housing
4. outdoor manure stores
5. manure application
6. grazing animals.

The emissions from housing include emissions from feeds other than silage. As feeding with silage can be a large source of NMVOCs, especially with regard to dairy cows, two different methodologies are given: one for 'dairy cows plus other cattle' and another for the 'remaining' livestock categories.

The methodology for dairy cattle and other cattle is based on feed intake. The methodology for other livestock categories is based on excreted volatile substances.

At present, few studies are described in the scientific literature that provide NMVOC emission estimates for housed livestock, manure storage and manure application together. Hence, EFs are not available to directly, and independently, estimate emissions of NMVOCs resulting from manure storage and manure application. However, a correlation between $NH_3$ emissions and many of the different NMVOCs emitted from livestock housing has been found ($r^2 \approx 0.5$) (Feilberg et al., 2010). Therefore, NMVOC emissions from manure stores and manure application are estimated as a fraction of those from livestock housing. This fraction is assumed to be the same ratio as for $NH_3$ emissions. This methodology could be biased, especially for manure application, because the NMVOCs are formed in the manure during storage and released after manure application. This is a different process from that of $NH_3$ because there is relatively little mineralisation of organic N to $NH_4^+$ during manure storage. Bias may also arise as NMVOCs calculated using this approach will not account for NMVOCs emitted at biogas plants during the storage of feedstocks and digestates.

**Dairy cattle and other cattle:**

$$E_{NMVOC} = AAP_{animal} \times (E_{NMVOC,silage\_store} + E_{NMVOC,silage\_feeding} + E_{NMVOC,hous} + E_{NMVOC,store} + E_{NMVOC,appl} + E_{NMVOC,graz}) \tag{48}$$

where:

$$E_{NMVOC,silage\_store} = MJ \times x_{house} \times (EF_{NMVOC,silage\_feeding} \times Frac_{silage}) \times Frac_{silage\_store} \tag{49}$$

$$E_{NMVOC,silage\_feeding} = MJ \times x_{hous} \times (EF_{NMVOC,silage\_feeding} \times Frac_{silage}) \tag{50}$$

$$E_{NMVOC,house} = MJ \times x_{hous} \times (EF_{NMVOC,house}) \tag{51}$$

$$E_{NMVOC,manure\_store} = E_{NMVOC,hous} \times (E_{NH3,storage\_}/E_{NH3,hous}) \tag{52}$$

$$E_{NMVOC,appl.} = E_{NMVOC,\ hous} \times (E_{NH3appl.}/E_{NH3hous}) \tag{53}$$

$$E_{NMVOC,graz} = MJ \times (1 - x_{hous}) \times EF_{NMVOC,graz} \tag{54}$$

where MJ is the gross feed intake in megajoules (MJ) per year.

Values of feed intake in MJ should, if possible, be country specific (refer to the format for annual reporting of greenhouse gases to the UNFCCC, Table 4.A). If the data from the UNFCCC are used they should be multiplied by 365 to obtain intake in MJ per year. If no country-specific data on feed intake in MJ are available, the default data given in the IPPC 2006 Guidelines should be used. The conversion between dry matter intake and MJ can be made by multiplying the amount of dry matter by 18.45 (IPCC, 2006, equation 10.24). The EFs are listed in Table 3.11.

The value for $x_{hous}$ is the proportion of the year the animals are housed. If no national data are available, refer to Table 3.9 for default values for the length of the housing period in days from which the proportions of time spent housed can be derived.

The $Frac_{silage}$ is the fraction of feed in dry matter during housing that is silage, out of the maximum proportion of silage possible in the feed composition. In practice, the maximum proportion of silage in dry matter is approximately 50 % of the total dry matter intake. If silage feeding is dominant, $Frac_{silage}$ should be 1.0.

The $Frac_{silage\_store}$ is the proportion of the emissions from the silage store compared with the emissions from the feeding table in the building. In practice, there is a relationship between the size of the silage store and the number of animals. In equation 51, it is assumed that these emissions are a fraction of the emissions from the feeding table, which again depends on its size and its emissions. A tentative default value of 0.25 is proposed for European conditions. This value of 0.25 is an average based on Alanis et al. (2008), Chung et al. (2010) and a temperature correction to account for typical European climatic conditions (Alanis et al., 2010).

$E_{NH3,storage}$, $E_{NH3,hous}$ and $E_{NH3appl.}$: $NH_3$ emissions.

**All livestock categories other than cattle:**

$$E_{NMVOC,silage\_store} = VS \times x_{hous} \times (EF_{NMVOC,\ silage\ feed} \times Frac_{silage}) \times Frac_{silage\_store} \qquad (55)$$

$$E_{NMVOC,silage\_feeding} = VS \times x_{hous} \times (EF_{NMVOC,silage\_feeding} \times Frac_{silage}) \qquad (56)$$

$$E_{NMVOC,hous} = VS \times x_{hous} \times (EF_{NMVOC,hous}) \qquad (57)$$

$$E_{NMVOC,manure\_store} = E_{NMVOC,hous} \times (E_{NH3,storage\_}/E_{NH3,\ hous}) \qquad (58)$$

$$E_{NMVOC,appl.} = E_{NMVOC,hous} \times (E_{NH3appl.}/E_{NH3hous}) \qquad (59)$$

$$E_{NMVOC,graz} = kg\ VS \times (1 - x_{hous}) \times EF_{NMVOC,graz} \qquad (60)$$

where kg VS is the excreted VS in kg per year for the livestock category, in kg per year.

The proportion of silage in the feed will vary by livestock species, among countries and between years. It is therefore good practice to provide an estimate for the proportion of silage used of the maximum feasible amount of silage in the feed.

Values for excreted VS in kg should preferably be country specific and refer to the annual reporting of greenhouse gases under the UNFCCC in Table 3.B(a)s1. If the data from the UNFCCC are used, they must be multiplied by 365 to obtain a value for VS excretion per year, since VS emissions are reported under UNFCCC as daily VS excretion values. If no country-specific data on VS excretion are available, it is recommended that the default data given in the IPPC 2006 Guidelines are used. The EFs are listed in Table 3.11.

### 3.4.3 Algorithm for particulate matter

A number of recent studies have demonstrated that there is still considerable variability in EFs among measurement programmes. In particular, studies carried out between 2006 and 2016 suggest that results from Takai (1998), which were used to give Tier 2 EFs in the *EMEP/EEA air pollutant emissions inventory guidebook 2013* (EMEP/EEA, 2013), are large by comparison with other results and may not represent typical current levels of PM emissions.

Countries are encouraged to develop country-specific EFs, taking into account information on the parameters presented in section 2.2.4. Information from the literature suggests that, for example, housing systems used to reduce $NH_3$ emissions may substantially increase emissions of PM. The reduction in PM emissions as a result of using air scrubbing in livestock housing can be taken into account by reducing the EF by the proportion by which PM emissions are reduced by the scrubbers. For the reasons given in section 2.1.4, PM emissions should not be affected by diverting a proportion of the manures for AD.

Annex 1, section A1.3.1, presents the EFs used to estimate Tier 1 EFs for all animals but pigs and poultry differentiated by type of manure management system (solid or liquid). However, a review of the scientific literature as a whole does not support the inclusion of a Tier 2 methodology.

### 3.4.4 Tier 2 emission factors

***Ammonia***

Table 3 shows the default $NH_3$-N EFs and the proportions of TAN in the manure excreted.

**Table 3.9 Default Tier 2 $NH_3$-N EFs and associated parameters for the Tier 2 methodology for the calculation of the $NH_3$-N emissions from manure management**

| Code | Livestock | Housing period (a), d $a^{-1}$ | $N_{ex}$ (b) | Proportion of TAN | Manure type | $EF_{housing}$ | $EF_{yard}$ | $EF_{storage}$ | $EF_{application}$ | $EF_{grazing/outdoor}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 3B1a | Dairy cattle | 180 | 105 | 0.6 | Slurry | 0.24 | 0.30 (e) | 0.25 | 0.55 | 0.14 |
| | | | | | Solid | 0.08 | 0.30 (e) | **0.32** | 0.68 | 0.14 |
| 3B1a | Dairy cattle, tied housing | 180 | 105 | 0.6 | Slurry | 0.09 | 0.30 (e) | 0.25 | 0.55 | 0.14 |
| | | | | | Solid | 0.09 | 0.30 (e) | 0.32 | 0.68 | 0.14 |
| 3B1b | Non-dairy cattle (all other cattle) | 180 | 41 | 0.6 | Slurry | 0.24 | 0.53 (e) | 0.25 | 0.55 | 0.14 |
| | | | | | Solid | 0.08 | 0.53 (e) | 0.32 | 0.68 | 0.14 |
| 3B2 | Sheep | 30 | 15.5 | 0.5 | Solid | 0.22 | 0.75 (e) | 0.32 | 0.90 | 0.09 |
| 3B33 | 'Swine' (finishing pigs, 8–110 kg) | 365 | 12.1 | 0.7 | Slurry | 0.27 | 0.53 (e) | 0.11 | 0.40 | |
| | | | | | Solid | 0.23 | 0.53 (e) | 0.29 | 0.45 | |
| 3B3 | 'Swine' (sows and piglets to 8 kg) | 365 | 34.5 | 0.7 | Slurry | 0.35 | NA | 0.11 | 0.29 | |
| | | | | | Solid | 0.24 | NA | 0.29 | 0.45 | |
| | | 0 | | | Outdoor (d) | NA | NA | NA | NA | 0.31 (d) |
| 3B4a | Buffalo(c) | 140 | 82.0 (e) | 0.5 | Solid | 0.20 | NA | 0.17 | 0.55 | 0.14 |
| 3B4d | Goats) | 30 | 15.5 | 0.5 | Solid | 0.22 | 0.75 (e) | 0.28 | 0.90 | 0.09 |
| 3B4e,3B4f | Horses (and mules, asses) | 180 | 47.5 | 0.6 | Solid | 0.22 | NA | 0.35 | 0.90 (e) | 0.35 |
| 3B4gi | Laying hens (laying hens and parents) | 365 | 0.77 | 0.7 | Solid, can be stacked | 0.20 | NA | 0.08 | 0.45 | |
| 3B4gi | Laying hens (laying hens and parents) | 365 | 0.77 | 0.7 | Slurry, can be pumped | 0.41 | NA | 0.14 | 0.69 | |
| 3B4gii | Broilers (broilers and parents) | 365 | 0.36 | 0.7 | Solid | 0.21 | NA | 0.30 | 0.38 | |
| 3B4giii | Turkeys | 365 | 1.64 | 0.7 | Solid | 0.35 | NA | 0.24 | 0.54 | |
| 3B4giv | Other poultry (ducks) | 365 | 1.26 | 0.7 | Solid | 0.24 | NA | 0.24 | 0.54 | |
| 3B4giv | Other poultry (geese) | 365 | 0.55 (f) | 0.7 | Solid | 0.57 | NA | 0.16 | 0.45 | |
| 3B4h | Other animals (fur animals(g)) | 365 | 4.60 (c) | 0.6 | Solid | 0.27 | NA | 0.09 | NA | |

**Notes**: EFs are given as a proportion of TAN.

**Sources**: Default EFs for all cattle and all pigs and for layers and broilers have been derived from published values as reported in annex 1. Default EFs for sheep, goats, horses, asses and mules, turkeys, ducks, geese and other animals are from the European Agricultural Gaseous Emissions Inventory Researchers (EAGER) network (http://www.eager.ch/) (Reidy et al., 2007; 2009, and references cited therein)

(a) The housing period is the number of days the livestock are kept in buildings. For some livestock, mainly dairy cows, the yards will also be used during the grazing period, e.g. when the cows come to the farm to be milked. The housing period is used to determine the proportion of N excretion that is deposited within buildings and hence used to calculate emissions during housing and also the subsequent emissions from manure stores and following application of manure to land.

(b) Default N excretion data were taken from Table 10.19, Chapter 10, of IPCC, 2006.

(c) Taken from EAGER.

(d) Sows and weaned pigs (weaners) up to 30-35 kg live-weight are kept in outdoors in fields with small huts for shelter.

(e) Taken from NARSES (Webb and Misselbrook, 2004).

(f) From Rösemann et al. (2015).
(g) A 'fur animal' is any animal raised and slaughtered only for its fur.

The values for the proportion of TAN were the average from EAGER comparisons (Reidy et al., 2007, and expert judgement). The national EFs from which the values were derived are given in Annex 1, Table A1.8.

**Table 3.10. Default emission factors for losses of N in gasses other than ammonia**

| | kg of N in NO or $N_2$ (kg TAN)$^{-1}$ |
|---|---|
| EFstorage_slurry NO | 0.0001 |
| EFstorage_slurry $N_2$ | 0.0030 |
| EFstorage_solid NO | 0.0100 |
| EFstorage_solid $N_2$ | 0.3000 |

**Source**: Misselbrook et al., 2015

***Non-methane volatile organic compounds***

NMVOC Tier 2 EFs are based on measurements from the NAEM study (US EPA, 2012). These findings have been adjusted to reflect agricultural conditions in western Europe (See annex 1, sections A1.2.1 and A1.2.2, for details). It is good practice for all countries to use country-specific activity data if available.

The results from the NAEM study allow the estimation of NMVOC emissions only during housing. The calculation of emissions from the other sources, i.e. silage storage, silage feeding, storage of manure and application of manure, is based on fractions of emission from housing (Alanis et al., 2008, 2010; Chung et al., 2010). The emissions from grazing animals are based on measurements made by Shaw et al. (2007).

The emissions during housing are estimated as an average of NMVOC emissions and non-methane hydrocarbon (NMHC) emissions. The NMHC measurements are converted to NMVOC emissions. For broilers and finishers, the emission estimates are converted to ‘per 500 kg animal’ values, as the measurements cover a wide range of animal weights. These average data were then converted to western European production levels based on the IPCC 2006 guidelines (IPCC, 2006) and other default values in this guidebook.

The NAEM study included emissions from feeding tables, enteric fermentation and manure stored inside livestock housing. These measurements have been split into emissions from feeding with silage and feeding without silage based on data from Alanis et al. (2008) and Chung et al. (2010).

The NAEM study covered a wide range of climatic conditions. The measured data are highly variable and it has not been feasible to include temperature correction functions for the different climatic conditions found in the EMEP area. The proposed EFs are therefore averages without corrections for climatic conditions, except for emissions from silage stores for which a temperature correction factor from 20 °C to 10 °C has been made (Alanis et al., 2010).

**Table 3.11 Default NMVOC Tier 2 EFs for dairy cattle and other cattle ([a])**

| | | $EF_{NMVOC,silage\_feeding}$ | $EF_{NMVOC,hous}$ | $EF_{NMVOC,graz}$ |
|---|---|---|---|---|
| **Code** | **Livestock** | **kg NMVOC kg/MJ feed intake** | | |
| 3B1a | Dairy cattle | 0.0002002 | 0.0000353 | 0.0000069 |
| 3B1b | Non-dairy cattle ([b]) | 0.0002002 | 0.0000353 | 0.0000069 |

(a) Data from the NAEM study (US EPA, 2012) converted to European conditions.
(b) Includes young cattle, beef cattle and suckling cows.

**Table 3.12 Default NMVOC Tier 2 EFs for livestock categories other than cattle (a)**

| | | $EF_{NMVOC,silage\ feed.}$ | $EF_{NMVOC,building}$ | $EF_{NMVOC,graz}$ |
|---|---|---|---|---|
| **Code** | **Livestock** | **kg NMVOC/kg VS excreted** | | |
| 3B2 | Sheep | 0.010760 | 0.001614 | 0.00002349 |
| 3B3 | 'Swine' (finishing pigs (b)) | | 0.001703 | |
| 3B3 | 'Swine' (sows + piglets to 8 kg) | | 0.007042 | |
| 3B4a | Buffalo (c) | 0.010760 | 0.001614 | 0.00002349 |
| 3B4d | Goats (c) | 0.010760 | 0.001614 | 0.00002349 |
| 3B4e | Horses (c) | 0.010760 | 0.001614 | 0.00002349 |
| 3B4f | Mules and asses (c) | 0.010760 | 0.001614 | 0.00002349 |
| 3B4gi | Laying hens (laying hens and parents) | | 0.005684 | |
| 3B4gii | Broilers (broilers and parents) | | 0.009147 | |
| 3B4giii | Turkeys[4] | | 0.005684 | |
| 3B4giv | Other poultry (ducks, geese) (d) | | 0.005684 | |
| 3B4h | Other animals (fur animals) | | 0.005684 | |
| 3B4h | Other animals (rabbits) (c) | | 0.001614 | |
| 3B4h | Other animals (reindeer) (c) | | 0.001614 | 0.00002349 |

(a) Data from the NAEM study (US EPA, 2012) converted to account for European conditions.

(b) Includes pigs from 8 kg to slaughtering.

(c) Based on data for sheep.

(d) Based on data for layers.

***Particulate matter***

PM emissions depend on, among other things, the factors discussed in annex 1, section A1.2.2. The available literature does not allow the estimation of EFs that take account of the impact of the above-mentioned variables.

### *3.4.5 Activity data*

**Time spent in yard areas**

The inclusion of emissions resulting from livestock in yard areas does complicate the calculation since, in most cases, livestock will spend only a few hours per day in yards and spend the rest of the day in the building, grazing or both. Hence, the length of the housing period, expressed in days, will need to be reduced to account for the total time estimated to be spent in yards, so that the proportions of $x_{hous}$, $x_{yards}$ and $x_{graz}$ add up to 1.0. For example, if dairy cows are estimated to spend 25 % of their time in collecting yards before and after milking, both the housing and grazing periods need to be reduced by 25 % to accurately estimate $x_{hous}$ and $x_{graz}$. Data on the proportions of the day that livestock spend in open yard areas may not be available. In the absence of country-specific data, the value of 25 % of daily TAN deposited to yards by dairy cows, cited by Webb and Misselbrook (2004; see Figure 1 of Webb and Misselbrook, 2004), may be used.

**Housing, manure storage and grazing, manure treatment and manure application**

Activity data should be gathered from national farming statistics and farm practice surveys. Of particular importance are estimates of N excretion, the length of the grazing period for ruminants and the type of store.

Table 3.13 describes the manure storage systems referred to in this chapter and makes comparisons with the definitions of manure management systems used by the IPCC.

**Table 3.13 Comparison of manure storage type definitions used here and those used by the IPCC**

| Term | Definition | IPCC equivalent |
|---|---|---|
| Lagoons | Storage with a large surface area to depth ratio; normally shallow excavations in the soil | Liquid/slurry<br>Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the building housing livestock, usually for periods of less than 1 year |
| Tanks | Storage with a low surface area to depth ratio; normally steel or concrete cylinders | |
| Heaps | Piles of solid manure | Solid storage<br>The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked because of the presence of a sufficient amount of bedding material or loss of moisture by evaporation |
| In-house slurry pit | Mixture of excreta and washing water, stored within the building housing livestock, usually below the confined animals | Pit storage below animal confinements<br>Collection and storage of manure usually with little or no added water, typically below a slatted floor in an enclosed livestock confinement facility, usually for periods of less than 1 year |
| In-house deep litter | Mixture of excreta and bedding, accumulated on the floor of the building housing livestock | Cattle and pig deep bedding<br>As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system is also known as a bedded pack manure management system |
| Crust | Natural or artificial layer on the surface of slurry which reduces the diffusion of gasses to the atmosphere | No definition given |
| Cover | Rigid or flexible structure that covers the manure and is impermeable to water and gasses | No definition given |
| Composting, passive windrow | Aerobic decomposition of manure without forced ventilation | Composting, static pile<br>Composting in piles with forced aeration but no mixing |
| Forced-aeration composting | Aerobic decomposition of manure with forced ventilation | Composting, in-vessel<br>Composting in piles with forced aeration but no mixing |
| Biogas treatment | Anaerobic fermentation of slurry and/or solid | Anaerobic digester<br>Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel or covered lagoon. Digesters are designed and operated for waste stabilisation by the microbial reduction of complex organic compounds to $CO_2$ and $CH_4$, which is captured and flared or used as a fuel |
| Slurry separation | The separation of the solid and liquid components of slurry | No definition given |
| Acidification | The addition of strong acid to reduce manure pH | No definition given |

Note: $CH_4$, methane; $CO_2$, carbon dioxide.

## 3.5 Tier 3 emission modelling and the use of facility data

There is no restriction on the form of Tier 3, provided it can supply estimates that can be demonstrated to be more accurate than Tier 2. If data are available, emission calculations may be made for a greater number of livestock categories than listed under Tier 2 (but see subsection 4.2). Mass-balance models developed by the reporting country may be used in preference to the structure proposed here. A Tier 3 method might also utilise the calculation procedure outlined under Tier 2, but with the use of country-specific EFs or the inclusion of abatement measures. The effect of some abatement measures can be adequately described using a reduction factor (RF), i.e. a proportional reduction in the emission estimate for the unabated situation, together with the proportion of the source to which the abatement technique is applied ($P_{\_abate}$). For example, if $NH_3$ emissions from animal housing were reduced by using partially slatted flooring instead of fully slatted flooring, and this technique is applied to 20% of the housing stock, equation 15 (see subsection 3.4.1) could be modified as follows:

$$E_{hous\_slurry} = m_{hous\_slurry\_TAN} \times RF \times P_{\_abate} \times EF_{hous\_slurry} \qquad (61)$$

However, users need to be aware that the introduction of abatement measures may require the modification of EFs for compounds other than the target pollutant. For example, covering a slurry store may also alter $N_2$ and $N_2O$ emissions, and therefore amendments to their relevant EFs would also be required. The Tier 2 equations will require further amendment if abatement techniques that remove N from the manure management system are employed, e.g. biofilters that clean the exhaust air from livestock housing which denitrify captured N. If N is removed by air scrubbing by dissolving the $NH_3$, and if this N solution is added to the slurry store or applied directly, it must be accounted for as an additional amount of N at another stage.

Tier 3 methods must be well documented in order to clearly describe estimation procedures and must be accompanied by supporting literature.

## 3.6 Technical support

A worked example of the use of these steps is provided in the accompanying spreadsheet file to this chapter, available from the EMEP/EEA guidebook 2019 website (http://eea.europa.eu/emep-eea-guidebook.

# 4 Data quality

## 4.1 Completeness

A complete inventory should estimate $NH_3$, NO, PM and NMVOC emissions from all systems of manure management for all livestock categories. To make Tier 2 estimates of $NH_3$ emissions losses of all N species from livestock housing, emissions from open yard areas and manure stores need to be calculated. Population data should be cross-checked among the main reporting mechanisms (such as national agricultural statistics databases and Eurostat) to ensure that the information used in the inventory is complete and consistent. Because of the widespread availability of the FAO database of livestock information, most countries should be able to prepare, at a minimum, Tier 1 estimates for the major livestock categories. For more information regarding the completeness of livestock characterisation, see IPCC, 2006 (section 10.2).

## 4.2 Avoiding double counting with other sectors

In cases in which it is possible to split these emissions among manure management sub-categories within the livestock categories, it is good practice to do so. However, care must be taken that the emissions are not double counted. This may occur if emissions are reported from outdoor yard areas without making appropriate reductions in emissions from livestock housing or grazed pastures.

## 4.3 Verification

Documentation, detailing when and where the agricultural inventory was checked and by whom, should be included.

Dry and wet deposition or ambient atmospheric concentration time series which support or contradict the inventory should be discussed.

## 4.4 Developing a consistent time series and recalculation

General guidance on developing a consistent time series is given in Part A Chapter 4 of this guidebook – 'Time series consistency'.

Developing a consistent time series of emission estimates for this source category requires, at a minimum, the collection of an internally consistent time series of livestock population statistics. General guidance on the development of a consistent time series is addressed in Part A (the general guidance chapters), Chapter 4 'Time series consistency', of the Guidebook (EMEP/EEA, 2019). Under current IPCC guidance (IPCC, 2006), the other two activity data sets required for this source category (i.e. N excretion rates and manure management system usage data), as well as the manure management EF, will be kept constant for the entire time series. However, if using a Tier 2 or Tier 3 approach to calculating $NH_3$ emissions, in which emissions are estimated as a proportion of TAN excreted, it will be necessary to make reliable estimates of N excretion for each year of the time series, since these N excretions, and/or the proportions of TAN, may change over time. For example, milk yield and live weight gain may increase with time, and farmers may alter livestock feeding practices which could affect N excretion rates. Furthermore, the livestock categories in a census may change. A particular system of manure management may change because of operational practices or new technologies such that a revised EF is warranted. These changes in practices may be due to the implementation of explicit emission reduction measures, or may be due to changing agricultural practices without regard to emissions. Regardless of the driver of change, the parameters and EF used to estimate emissions must reflect the change. The inventory text should thoroughly explain how the change in farm practices or the implementation of mitigation measures has affected the time series of activity data or EFs. Projections need to take account of likely changes in agricultural activities, not just changes in livestock numbers, but also changes in manure application times and methods due, for example, to the need to introduce manure management measures to comply with the Nitrates Directive, the IPPC and the Water Framework Directive.

## 4.5 Uncertainty assessment

General guidance on quantifying uncertainties in emission estimates is given in Chapter 5, 'Uncertainties', of the Guidebook (EMEP/EEA, 2019). In the following sections, the results of some previous studies of uncertainties in emission estimates from agricultural sources are reported.

### *4.5.1 Emission factor uncertainties*

***Ammonia***

Uncertainties with regard to $NH_3$ EFs vary considerably. A study in the United Kingdom (Webb and Misselbrook, 2004), in which a distribution was attached to each of the model inputs (activity or EF data), based on the distribution of raw data (or if no or only single estimates existed, on expert assumptions) indicated an uncertainty range from ±14 %, for the EF for slurry application, to ±136 %, for beef cattle grazing. In general, EFs for the larger sources tended to be based on a greater number of measurements than those for smaller sources and, as a consequence, tended to be more certain. The exceptions were the EFs for buildings in which livestock were housed on straw and grazing EFs for beef cattle and sheep. The uncertainties related to the partial EFs have yet to be discussed. The overall uncertainty for the United Kingdom $NH_3$ emissions inventory, as calculated using a Tier 3 approach, was ±21 % (Webb and Misselbrook, 2004), while that for the Netherlands, also calculated using a Tier 3 approach, was ±25 % (Wever et al., 2018, cited in Bruggen et al., 2018).

***Nitric oxide***

Although the principles of the bacterial processes leading to NO emissions (nitrification and denitrification) are reasonably well understood, it is still difficult to quantify nitrification and denitrification rates in livestock manures. In addition, the observed fluxes of NO show large temporal and spatial variations. Consequently, there are large uncertainties associated with current estimates of emissions for this source category (–50 % to +100 %). Accurate and well-designed emission measurements from well characterised types of manure and manure management systems can help reduce these uncertainties. These measurements must account for temperature, moisture conditions, aeration, manure N content, metabolisable carbon, duration of storage and other aspects of treatment.

***Non-methane volatile organic compounds***

The EFs included are initial estimates and, as such, provide only broad indications of the likely range. The uncertainties associated with these EFs are very high. Furthermore, given the many different compounds, the large variation in chemical and physical properties, the wide variations in conditions in which they are formed and the applicability of measured emissions for one species to other species will result in large uncertainties.

***Particulate matter***

The EFs are only an initial estimate and, as such, provide only a broad indication of uncertainty. The variability presented in the recent studies suggests a particularly large uncertainty for the EFs that impact on the emission estimates. Further uncertainties may arise for livestock categories other than poultry with regard to determining the amount of time spent housed, and the proportion of animals to which this applies.

### *4.5.2 Activity data uncertainties*

There is likely to be greater uncertainty in estimates of activity data, although, for such data, a quantitative assessment of uncertainty is difficult to determine. Webb and Misselbrook (2004) reported that 8 of the 10 input data sets to which estimates of United Kingdom $NH_3$ emissions were the most sensitive were activity data. Uncertainty ranges for the default N excretion rates used for the IPCC calculation of $N_2O$ emissions were estimated at about +50 % (source: judgement by IPCC Expert Group). However, for some countries, the uncertainty will be less. Webb (2000) reported uncertainties for United Kingdom estimates of N excretion to range from ±7 % for sheep to ±30 % for pigs. Livestock numbers, (partial) EFs and frequency distributions are likely to be biased; data sets are often incomplete. For this edition of the Guidebook, no quality statements can be given other than those mentioned above. However, experts compiling livestock numbers, national 'expert judgement' estimates for EFs and frequency distributions are strongly advised to document their findings, decisions and calculations in order to facilitate the review of the corresponding inventories.

The first step in collecting data on livestock numbers should be to investigate existing national statistics, industry sources, research studies and FAO statistics. The uncertainty associated with populations will vary widely depending on source, but should be known within ±20 %. Often, national livestock population statistics already have associated uncertainty estimates, in which case these should be used. If published data are not available from these sources, interviews of key industry and academic experts should be undertaken.

## 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 Part A, Chapter 6, 'Inventory management, improvement and QA/QC', of this Guidebook (EMEP/EEA, 2019)

It is good practice to ensure that the dietary information used in the calculation of N excretion is compatible with that used in the calculation of dry matter intake, as used in section 10.2.2 of the 2006 IPCC Guidelines (IPCC, 2006).

**Activity data check**

- The inventory agency should review livestock data collection methods, in particular checking that livestock category data were collected and aggregated correctly with consideration for the duration of production cycles. The data should be cross-checked with previous years to ensure the data are reasonable and consistent with reported trends. Inventory agencies should document data collection methods, identify potential areas of bias and evaluate the representativeness of the data.
- Manure management system allocation should be reviewed on a regular basis to determine if changes in the livestock industry are being captured. Conversion from one type of management system to another, and technical modifications to system configuration and performance, should be captured in the system modelling for the affected livestock.
- National agricultural policy and regulations may have an effect on parameters that are used to calculate manure emissions, and should be reviewed regularly to determine what impact they may have. For example, guidelines to reduce manure runoff into water bodies may cause a change in management practices, and thus affect the N distribution for a particular livestock

category. Consistency should be maintained between the inventory and ongoing changes in agricultural practices.

- If using country-specific data for N excretion, the inventory agency should compare these values with the IPCC default values. Significant differences, data sources and methods of data derivation should be documented.
- The N excretion rates, whether default or country-specific values, should be consistent with feed intake data as determined through animal nutrition analyses.
- Country-specific data for feed intake in MJ and for the excretion of volatile substance used in the estimation of NMVOC emissions should be compared with the IPCC default values. Significant differences, data sources and methods of data derivation should be documented. Data on the degree of silage feeding should be gathered as this is a crucial factor for estimating NMVOC emissions.

**Review of emission factors**

- The inventory agency should evaluate how well the implied EFs compare with alternative national data sources and with data from other countries with similar livestock practices. Significant differences should be investigated.
- If using country-specific EFs, the inventory agency should compare them with the default factors and note differences. The development of country-specific EFs should be explained and documented, and the results peer reviewed by independent experts.
- Whenever possible, available measurement data, even if they represent only a small sample of systems, should be reviewed relative to assumptions for $NH_3$, NO and NMVOC emission estimates. Representative measurement data may provide insights into how well current assumptions predict $NH_3$, $N_2O$ and NO emissions from manure management systems in the inventory area, and how certain factors (e.g. feed intake, system configuration, retention time) affect emissions. Because of the relatively small amount of measurement data available for these systems worldwide, any new results can improve the understanding of these emissions and possibly their prediction.

**External review**

The inventory agency should utilise experts in manure management and livestock nutrition to conduct expert peer reviews of the methods and data used. Although these experts may not be familiar with gaseous emissions, their knowledge of key input parameters for the emission calculation can aid in the overall verification of the emissions. For example, livestock nutritionists can evaluate N production rates to see if they are consistent with feed utilisation research for certain livestock species. Practising farmers can provide insights into actual manure management techniques, such as storage times and mixed-system usage. Wherever possible, these experts should be completely independent of the inventory process, in order to allow a true external review. If country-specific EFs, fractions of N losses, N excretion rates or manure management system usage data have been used, the derivation of or references for these data should be clearly documented and reported along with the inventory results under the appropriate source category. As a quality control, a N balance should be calculated, i.e. the total input of N (total amount of N in animal excretions plus total amount in bedding) should match the output of N (total of all emissions and N inputs to the soil).

## 4.7 Gridding

***Ammonia***

The EMEP requires $NH_3$ emissions to be gridded in order to calculate the transport of $NH_3$ and its reaction products in the air. Considering the potential for $NH_3$ to have local effects on ecology, $NH_3$ emission estimates should be disaggregated as much as possible. Given the dominance of livestock husbandry in the context of the emission of $NH_3$ in Europe, disaggregation is normally based on livestock census data. Spatial disaggregation of emissions from livestock manure management systems may be possible if the spatial distribution of the livestock population is known.

With respect to the modelling of atmospheric transport, transformation and deposition, a very high spatial resolution is desirable. However, the calculation procedures described in this guidebook may allow for a resolution in time of months, and may distinguish months of grazing and manure application from the rest of the year.

***Nitric oxide***

Spatial disaggregation of emissions from livestock manure management systems may be possible if the spatial distribution of the livestock population is known.

***Non-methane volatile organic compounds***

The Tier 1 methodology will provide spatially resolved emission data for NMVOCs on the scale for which matching activity data and frequency distributions of livestock housing, storage systems and grazing times are available.

***Particulate matter***

Spatial disaggregation of emissions from livestock production may be possible if the spatial distribution of the livestock population is known.

## 4.8 Reporting and documentation

There are no specific issues related to reporting and documentation.

# 5 Glossary

| | |
|---|---|
| AAP | Average annual population |
| AD | Anaerobic digestion |
| CRF | Common reporting format |
| EAGER | European Agricultural Gaseous Emissions Inventory Researchers Network |
| EF | Emission factor |
| FAO | Food and Agriculture Organization of the United Nations |
| FYM | Farmyard manure |
| GAINS | Greenhouse Gas and Air Pollution Interactions and Synergies |
| IIASA | International Institute for Applied Systems Analysis |
| IPCC | Intergovernmental Panel on Climate Change |

| | |
|---|---|
| LMMS | Livestock manure management system |
| LU | Livestock unit |
| MJ | Megajoules |
| NAEM | National Air Emissions Monitoring |
| NFR | Nomenclature for Reporting |
| NMHC | Non-methane hydrocarbon |
| ROG | Reactive organic gas |
| TMR | Total mixed ration |
| TAN | Total ammoniacal nitrogen |
| VFA | Volatile fatty acid |

# 6 References

Alanis, P., Sorenson, M., Beene, M., Krauter, C., Shamp, B. and Hason, A.S., 2008. 'Measurement of non-enteric emission fluxes of volatile fatty acids from a California dairy by solid phase micr-extraction with gas chromatography/mass spectrometry', *Atmospheric Environment*, (42) 6417–6424.

Alanis, P., Ashkan, S., Krauter, C. Campbell, S. and Hasson, A. S., 2010, 'Emissions of volatile fatty acids from feed at dairy facilities', *Atmospheric Environment*, (44) 5084–5092.

Bruggen, C. van, Bannink, A., Groenestein, C. M., Huijsmans, J. F. M., Lagerwerf, L. A., Luesink, H.H., van der Sluis, S. M., Velthof, G. L. and Vonk, J., 2018, 'Emissions into the atmosphere from agricultural activities in 2016. Calculations using the NEMA model', Wageningen, The Statutory Research Tasks Unit for Nature and the Environment (WOT Natuur & Milieu). WOt-technical report, (119) 124 pp.

Calvet, S., van den Weghe, H., Kosch, R. and Estellés, F., 2009, 'The influence of the lighting program on broiler activity and dust production', *Poultry Science*, (88) 2504–2511.

Chardon, W. J., and van der Hoek, K. W., 2002, *Berekeningsmethode voor de emissie van fijn stof vanuit de landbouw* [*Calculation method for emission of fine dust from agriculture*], Alterra/RIVM, Wageningen, the Netherlands.

Chung, M. Y., Beene, M., Ashkan, S., Krauter, C. and Hasson, A. S., 2010, 'Evaluation of non-enteric sources of non-methane volatile organic compounds (NMVOC) emissions from dairies', *Atmospheric Environment*, (44) 786–794.

Citepa, 2015, *Inventaire des émissions de polluants atmosphériques en France métropolitaine, format CEE-NU,* Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique, CITEPA, édition mars 2015, *(http://www.actu-environnement.com/media/pdf/news-25248-secten-ges.pdf)* accessed 30 September 2016.

Costa, A. and Guarino, M., 2009, 'Definition of yearly emission factor of dust and greenhouse gases through continuous measurements in swine husbandry', *Atmospheric Environment*, (43) 1548–1556.

Dämmgen, U. and Hutchings, N. J., 2008, 'Emissions of gaseous nitrogen species from manure management — A new approach', *Environmental Pollution,* (154) 488–497.

Dämmgen, U., Lüttich, M., Haenel, H-D., Döhler, H., Eurich-Menden, B. and Osterburg, B., 2007, '*Calculations of emissions from German agriculture — National Emission Inventory Report (NIR) 2008 for 2006*' (http://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/zip/deu_2008_nir_13may.zip), accessed 30 September 2016.

Demmers, T. G. M., Saponja, A., Thomas, R., Phillips, G. J., McDonald, A. G., Stagg, S., Bowry, A. and Nemitz, E., 2010, 'Dust and ammonia emissions from UK poultry houses', in: *XVII-th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)*, Québec City, Canada.

Dunlop, M., Ristovski, Z. D., Gallagher, E., Parcsi, G., Modini, R. L., Agranovski, V. and Stuetz, R. M., 2013, 'Odour, dust and non-methane volatile organic-compound emissions from tunnel-ventilated layer-chicken sheds: a case study of two farms', *Animal Production Science*, (53) 1309–1318.

EMEP/EEA, 2013, *EMEP/EEA air pollutant emission inventory guidebook — Technical guidance to prepare national emission inventories*, EEA Technical Report No 12/2013, European Environment Agency (http://www.eea.europa.eu/publications/emep-eea-guidebook-2013), accessed 30 September 2016.

EMEP/EEA, 2016, *EMEP/EEA air pollutant emission inventory guidebook — Technical guidance to prepare national emission inventories*, EEA Technical Report No 12/2013, European Environment Agency (http://www.eea.europa.eu/emep-eea-guidebook), accessed 30 September 2016.

EMEP/EEA, 2019, *EMEP/EEA air pollutant emission inventory guidebook — Technical guidance to prepare national emission inventories*, European Environment Agency (http://www.eea.europa.eu/emep-eea-guidebook), accessed 30 September 2019.

Eurostat, (http://ec.europa.eu/eurostat), European Commission DG Eurostat, accessed 30 September 2016.

Fabbri, C., Valli, L., Guarino, M., Costa, A. and Mazzotta, V., 2007, 'Ammonia, methane, nitrous oxide and particulate matter emissions from two different buildings for laying hens', *Biosystems Engineering*, (97) 441–455.

FAO, 2014, FAO Statistical Yearbook 2014, Food and Agriculture Organization of the United Nations (http://www.fao.org/3/a-i3590e.pdf) accessed 30 September 2016.

Feilberg, A., Liu, D., Adamsen, A. P., Hansen, M. J. and Jonassen, K. E., 2010, 'Odorant Emissions from Intensive Pig Production Measured by Online Proton-Transfer-Reaction Mass Spectrometry', *Environmental Science & Technology*, (44) 5894–5900.

Haeussermannn, A., Hartung, E., Gallmann, E., and Jungbluth, T., 2006, 'Influence of season, ventilation strategy, and slurry removal on methane emissions from pig houses', *Agriculture Ecosystems and Environment*, (112) 115–121.

Haeussermannn, A., Costa, A., Aerts, J. M., Hartung, E., Jungbluth, T., Guarino, M. and Berckmans, D., 2008, 'Development of a dynamic model to predict PM10 emissions from swine houses', *Journal of Environmental Quality*, (37) 557–564.

Hayes, M. D., Xin, H., Li, H., Shepherd, T. A., Zhao, Y. and Stinn, J. P., 2013, 'Ammonia, greenhouse gas, and particulate matter emissions of aviary layer houses in the Midwestern U.S.', *Transactions of the American Society of Agricultural and Biological Engineers,* (56) 1921–1932.

Hobbs, P. J., Webb, J., Mottram, T. T., Grant, B. and Misselbrook, T. M., 2004, 'Emissions of volatile organic compounds originating from UK livestock agriculture', *Journal of the Science of Food and Agriculture*, (84) 1414–1420.

Hutchings, N. J., Sommer, S. G., Andersen, J. M. and Asman, W. A. H., 2001, 'A detailed ammonia emission inventory for Denmark', *Atmospheric Environment,* (35) 1959–1968.

IPCC, 2006, 'Emissions from livestock and manure management', in: *2006 IPCC guidelines for national greenhouse gas inventories — Volume 4: Agriculture, forestry and other land use*, Intergovernmental Panel on Climate Change

(http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf).

Jacobson, L. D., Hetchler, B. P. and Johnson, V. J., 2004, 'Particulate emissions from pig, poultry, and dairy facilities located in Minnesota', in: *Proceedings of the AgEng 2004 'Engineering the Future' conference*, September 2004, Leuven, Belgium, 12–16.

Kirchmann, H. and Witter, E., 1989, 'Ammonia volatilization during aerobic and anaerobic manure decomposition', *Plant and Soil,* (115) 35–41.

Lacey, R. E., Redwine, J. S. and Parnell Jr, C. B., 2003, 'Particulate matter and ammonia emission factors for tunnel-ventilated broiler production houses in the southern U.S.', *Transactions of the American Society of Agricultural and Biological Engineers,* (460) 1203–1214.

Lim, T. T., Heber, A. J., Ni, J.-Q., Gallien, J. Z. and Xin, H., 2003, 'Air quality measurements at a laying hen house: Particulate matter concentrations and emissions', in: Keener, H. (ed.), *Air Pollution from Agricultural Operations III, Proceedings of the 12–15 October 2003 Conference*, ASAE, St. Joseph, MI, 249–256.

Misselbrook, T. H., Gilhespy, S. L., Cardenas, L. M., Williams, J. and Dragosits, U., 2015, *Ammonia Emissions from UK Agriculture — 2014*, Inventory Submission Report November 2015, DEFRA Contract SCF0102, Department for Environment, Food & Rural Affairs, p. 38.

Modini, R. L., Agranovski, V., Meyer, N. K., Gallagher, E., Dunlop, M. and Ristovski, Z. D., 2010. 'Dust emissions from a tunnel-ventilated broiler poultry shed with fresh and partially reused litter', *Animal Production Science,* (50) 552–556.

Mosquera, J. and Hol, J. M. G., 2011, 'Emissiefactoren methaan, lachgas en PM2.5 voor stalsystemen, inclusief toelichting', *Wageningen UR Livestock Research*, (496).

Mosquera, J., Hol, J. M. G., Winkel, A., Huis in 'T Veld, J. W. H., Dousma, F., Ogink, N. W. M. and Groenestein C. M., 2011, 'Fijnstofemissie uit stallen: nertsen', *Wageningen UR Livestock Research*, (340).

Redwine, J. S., Lacey, R. E., Mukhtar, S. and Carey, J. B., 2002, 'Concentration and emissions of ammonia and particulate matter in tunnel–ventilated broiler houses under summer conditions in Texas', *Transactions of the American Society of Agricultural Engineers*, (45) 1101–1109.

Reidy, B., Dämmgen, U., Döhler, H., Eurich-Menden, B., Evert, F. K. van, Hutchings, N. J., Luesink, H. H., Menzi, H., Misselbrook, T. H., Monteny, G.-J. and Webb, J., 2007, 'Comparison of models used for national agricultural ammonia emission inventories in Europe: Liquid manure systems', *Atmospheric Environment*, (42) 3452–3464.

Reidy, B., Webb, J., Monteny, G.-J., Misselbrook, T. H., Menzi, H., Luesink, H. H., Hutchings, N. J., Eurich-Menden, B., Döhler, H. and Dämmgen, U., 2009, 'Comparison of models used for national agricultural ammonia emission inventories in Europe: litter-based manure systems', *Atmospheric Environment*, (43) 1632–1640.

Rösemann C, Haenel H-D, Dämmgen U, Freibauer A, Wulf S, Eurich-Menden B, Döhler H, Schreiner C, Bauer B, Osterburg B, 2015, Calculations of gaseous and particulate emissions from German agriculture 1990 – 2013 : report on methods and data (RMD) submission 2015. Braunschweig: Johann Heinrich von Thünen Inst, 372 p, Thünen Rep 27.

Roumeliotis, T. S. and Van Heyst, B.J., 2007, 'Size fractionated particulate matter emissions from a broiler house in Southern Ontario, Canada', *Science of the Total Environment,* (383) 174–182.

Roumeliotis, T. S., Dixon, B. J. and Van Heyst, B. J., 2010, 'Characterization of gaseous pollutant and particulate matter emission rates from a commercial broiler operation part II: Correlated emission rates', *Atmospheric Environment,* (44) 3778–3786.

Seedorf, J. and Hartung, J., 2001, 'A proposal for calculating the dustlike particle emissions from livestock buildings', *Deutsch Tierarztliche Wochenschrift*, (108) 307–310.

Shaw, S., Mitloehner, F. M., Jackson, W., Depeters, E. J., Fadel, J. G., Robinson, P. H. Holtzinger, R. and Goldstein, A. H., 2007, 'Volatile Organic Compound Emissions from Dairy Cows and Their Waste as Measured by Proton-Transfer-Reaction Mass Spectrometry', *Environmental Science & Technology*, (41) 1310–1316

Shepherd, T. A., Zhao, Y., Li, H., Stinn, J. P., Hayes, M. D. and Xin, H., 2015, 'Environmental assessment of three egg production systems — Part II. Ammonia, greenhouse gas, and particulate matter emissions', *Poultry Science*, (94) 534–543.

Takai, H., Pedersen, S., Johnsen, J. O., Metz, J. H. M., Groot Koerkamp, P. W. G., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K. H. and Wathes, C. M., 1998, 'Concentrations and Emissions of Airborne Dust in Livestock Buildings in Northern Europe', *Journal of Agricultural Engineering Research*, (70) 59–77.

UNECE, 1991, 'Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution concerning the control of emissions of volatile organic compounds or their transboundary fluxes', United Nations Economic Commission for Europe (http://www.unece.org/env/lrtap/vola_h1.html).

US EPA, 2012, 'Nnational Air Emissions Monitoring Study, United States Environmental Protection Agency (https://www.epa.gov/afos-air/national-air-emissions-monitoring-study), accessed 30 September 2016.

Valli, L., Moscatelli, G. and Labartino, N., 2012, 'Ammonia and particulate matter emissions from an alternative housing system for laying hens', in: *Emissions of gas and dust from livestock (EmiLi 2012)*, Saint-Malo, France, 103–106.

Van Ransbeeck, N., Van Langenhove, H. and Demeyer, P., 2013, 'Indoor concentrations and emissions factors of particulate matter, ammonia and greenhouse gases for pig fattening facilities', *Biosystems Engineering,* (116) 518–528.

Webb, J., 2000, 'Estimating the potential for ammonia emissions from livestock excreta and manures', *Environmental Pollution*, (111) 395–406.

Webb, J. and Misselbrook, T. H., 2004, 'A mass-flow model of ammonia emissions from UK livestock production', *Atmospheric Environment*, (38) 2163–2176.

Winkel, A., Mosquera, J., Groot Koerkamp, P. W. G., Ogink, N. W. M. and Aarnink, A. J. A., 2015, 'Emissions of particulate matter from animal houses in the Netherlands', *Atmospheric Environment*, (111) 202–212.

# 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 (www.tfeip-secretariat.org/) for the contact details of the current expert panel leaders.

# Annex 1

## A1.1 Overview

### *A1.1.1 Ammonia*

There have been large reductions in emissions of sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) resulting from power generation, industry and transport since 1980. Consequently, within the next decade, $NH_3$ emissions are expected to account for more than a quarter of all acidifying, and half of all eutrophying, emissions of atmospheric pollutants in Europe. Approximately 90 % of the total $NH_3$ emissions in Europe originate from agriculture, and the remainder are from industrial sources, households, pet animals and natural ecosystems.

### *A1.1.2 Nitric oxide and di-nitrogen*

The processes of denitrification and nitrification, which release $N_2O$, also release NO and $N_2$. Whereas NO is a species reported as an air pollutant, estimates of $N_2$ emissions are only required to satisfy any mass balance calculation. Attempts to quantify NO emissions from manure storage show that these emissions are an order of magnitude of half the emissions of $N_2O$ from soils receiving mineral fertiliser or livestock manures (Haenel et al., 2016).

### *A1.1.3 Non-methane volatile organic compounds*

Emissions of NMVOCs from livestock husbandry originate from feed, especially silage, degradation of feed in the rumen, and partly digested and undigested fat, carbohydrate and protein decomposition in the rumen and in manure (Elliott-Martin et al., 1997; Amon et al., 2007; Alanis et al., 2008, 2010; Ngwabie et al., 2008; Feilberg et al., 2010; Parker et al., 2010; Trabue et al., 2010; Rumsey et al., 2012; Ni et al. 2012). Consequently, anything that affects the rate of feeding and manure management, such as the amount of formic acid added to silage, the management of silage heaps and livestock feeding, manure management during livestock housing and during storage, straw added to the manure and the duration of storage, and the technique used for manure application, will affect NMVOC emissions.

NMVOCs from feed are released from the open surface in the silage store or from the feeding table (Alanis et al., 2008, 2010; Chung et al., 2010), and NMVOCs formed in the rumen of animals are released through exhalation or via flatus (Elliott-Martin et al., 1997). NMVOCs formed in manure may be released inside the buildings housing livestock or from the surface of manure stores (Trabue et al., 2010; Parker et al., 2010). These emissions depend on the temperature and the wind speed over the surface. NMVOCs released after manure application and during grazing are likely to have been formed prior to application/deposition, within the animal or in the manure management system.

## A1.2 Description of sources

### A1.2.1 Process description

#### Ammonia

$NH_3$ volatilisation is essentially 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). $NH_3$ in solution is, in turn, maintained by the $NH_4^+$–$NH_3$ equilibrium (Equation A2):

$$NH_3\,(aq) \leftrightarrow NH_3\,(g) \tag{A1}$$

$$NH_4^+\,(aq) \leftrightarrow NH_3\,(aq) + H^+\,(aq) \tag{A2}$$

High pH (i.e. a low concentration of hydrogen ions ($H^+$) in solution) favours the right-hand side of the equilibrium shown in Equation A2, resulting in a greater concentration of $NH_3$ in solution and also, therefore, in the gaseous phase. Thus, if the system is buffered at values of less than c. pH 7 (in water), the dominant form of ammoniacal-N ($NH_x$) will be $NH_4^+$ and the potential for volatilisation will be small. In contrast, if the system 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 equilibriums may serve to increase or decrease this.

Typically, more than half of the N excreted by mammalian livestock is excreted in the urine, and between 65 and 85 % of urine-N is in the form of urea and other readily mineralised compounds (for information on ruminants, see Jarvis et al., 1989; for pigs, see Aarnink et al., 1997). Urea is rapidly hydrolysed by the enzyme urease to ammonium carbonate ($(NH_4)_2CO_3$) and ammonium ions ($NH_4^+$) provide the main source of $NH_3$. Ammonium-N ($NH_4^+$-N) and compounds that are readily broken down to $NH_4^+$-N, including uric acid, are referred to as TAN. In contrast, the majority of N in mammalian livestock faeces is not readily degradable (Van Faassen and Van Dijk, 1987); only a small percentage of this N is in the form of urea or $NH_4^+$ (Ettalla and Kreula, 1979) so $NH_3$ emissions are small enough (Petersen et al., 1998) for estimates of from housing to be based on urine-N, although TAN may be mineralised from faecal-N during manure storage. Poultry produce only faeces, a major constituent of which is uric acid and this, together with other labile compounds, may be degraded to $NH_4^+$-N after hydrolysis to urea (Groot Koerkamp, 1994).

Urease is widespread in soils and faeces and, consequently, the hydrolysis of urea is usually complete within a few days (Whitehead, 1990). Urine also contains other N compounds such as allantoin, which may be broken down to release $NH_3$ (Whitehead et al., 1989).

The $NH_4^+$ in manure is mainly found in solution or loosely bound to dry matter, in which it exists in equilibrium with dissolved $NH_3$. Since the usual analytical methods cannot distinguish between $NH_4^+$ and $NH_3$ in manure, it is common to refer to the combination ($NH_4^+$ plus $NH_3$) as TAN. Published studies have confirmed the relationship between $NH_3$ emissions and TAN (for cattle: Kellems et al. (1979), Paul et al. (1998), James et al. (1999), Smits et al. (1995); for pigs: Latimier and Dourmad (1993), Kay and Lee (1997), Cahn et al. (1998)).

#### Non-methane volatile organic compounds

There has been some uncertainty over which NMVOCs originate from different manure types and which from other sources, such as animal breath. However, less than 20 volatile compounds in total were measured in significant amounts from manures but at different concentrations or ratios in the headspace according to whether the manure was from pigs, cattle or poultry (Trabue et al., 2010; Ni et al., 2012; US EPA, 2012). NMVOCs collected from the headspace of manure may be affected by the nature of the adsorbent used and the means of desorption into the selected separation/detection system. Zahn et al. (1997) also recognised that some non-polar hydrocarbons are emitted from pig slurry lagoons. Their comprehensive study demonstrated that fluxes of NMVOCs from deep basin or pit manure storage systems were 500- to 5 700-times greater than those from biogenic sources. Both Parker et al. (2010) and Zahn et al. (1997) recognised that the NMVOCs identified by either small-scale laboratory studies or under conditions more representative of commercial farms did not necessarily represent the compounds produced in the field or their rates of emission. In addition, several VOCs were identified as originating from ruminant breath (Elliott-Martin et al., 1997; Hobbs et al., 2004; Spinhirne et al., 2003, 2004; Cai et al., 2006a). Emissions of NMVOCs are not a large source and are seen as a dysfunction of the rumen (Moss et al. 2000). Some NMVOCs, e.g. acetone, may be emitted by cattle if they are suffering from, for example, ketosis. Emissions of volatile fatty acids (VFAs), a form of NMVOCs not associated with proteins, and phenols appear to remain constant in manure stores over time (Patni et al., 1985). More than 200 NMVOCs derived from livestock feeding operations have been identified (Montes et al., 2010). Similar to other compounds, the emission of NMVOCs is dependent on the temperature and ventilation rate within buildings housing livestock (Parker et al., 2010, 2012).

Although more than 500 volatile compounds originating from cattle, pigs and poultry have been identified (Ni et al., 2012), there is considerable uncertainty concerning the organic precursors in each manure type, from which the NMVOCs originate. Emissions include alcohols, aldehydes, acids, sulphides and phenols and, in the case of pig slurry, indoles. Some of the major compounds are listed in Table A1.1. Recently, dimethyl sulphide (DMS) has been identified as originating from ruminant breath. Table A1.2 gives the percentage distribution of the most common NMVOCs found in the NAEM study, which includes NMVOC measurements from 16 different animal production units (US EPA, 2012).

**Table A1.1 Sources and processes of NMVOC formation**

| NMVOC | Precursor or process | |
|---|---|---|
| | Amino acids (a) | Process |
| Methanol | NA | Pectin demethylation |
| Ethanol | NA | Fermentation |
| Acetaldehyde | NA | Fermentation |
| Acetic acid | NA | Fermentation |
| Acetone | NA | Fat metabolism |
| Trimethylamine | All | Organic N methylation |
| 2-methyl propanoic acid | Valine | |
| 3-methyl butanoic acid | Isoleucine | |
| 2-methyl butanoic acid | Leucine | |
| Methanethiol | Methionine | |
| Dimethyl sulphide | Cysteine | |
| 4-methyl phenol | Tyrosine | |
| 4-ethyl phenol | Tyrosine | |
| Indole | Tryptophan | |
| 3-methyl indole | Tryptophan | |

Notes: 'NA' indicates no amino acid as source.

(a) Source: from Mackie et al. (1998).

**Table A1.2 Percentage distribution of different NMVOCs from buildings housing different animal types (estimated from US EPA, 2012)**

| Poultry | % | Cattle | % | Pigs | % |
|---|---|---|---|---|---|
| 2,3-Butanedione | 9.9 | 2,3-Butanedione | 0.3 | 2,3-Butanedione | 4.3 |
| Dimethyl disulphide | 5.1 | Dimethyl disulphide | 0.5 | Dimethyl disulphide | 1.0 |
| Acetaldehyde | 4.0 | Acetaldehyde | 6.7 | Acetaldehyde | 8.8 |
| 2-Butanone | 5.8 | 2-Butanone | 2.4 | 2-Butanone | 10.2 |
| Isopropanol | 23.0 | Isopropanol | 7.0 | Isopropanol | 19.3 |
| Pentane | 3.6 | Pentane | 3.4 | Pentane | 4.6 |
| Dimethyl sulphide | 2.8 | Dimethyl sulphide | 1.3 | Dimethyl sulphide | 3.7 |
| Acetic acid | 7.3 | Acetic acid | 2.9 | Acetic acid | 7.8 |
| Hexanal | 2.3 | Hexanal | 0.2 | Hexanal | 2.3 |
| Ethyl acetate | 0.4 | Ethyl acetate | 18.7 | Ethyl acetate | 2.1 |
| Hexane | 4.9 | Hexane | 0.3 | Hexane | 1.2 |
| Propionic acid | 1.7 | Propionic acid | 1.0 | Propionic acid | 7.1 |
| Pentanal | 1.8 | Pentanal | 0.2 | Pentanal | 2.5 |
| Phenol | 1.8 | Phenol | 1.0 | Phenol | 3.6 |
| 1-Butanol | 0.9 | 1-Butanol | 0.6 | 1-Butanol | 1.9 |
| 2-Pentatone | 0.9 | 2-Pentatone | 0.1 | 2-Pentatone | 0.9 |
| 4-Methyl-phenol | 1.2 | 4-Methyl-phenol | 1.2 | 4-Methyl-phenol | 6.0 |
| Butanoic acid | < 0.0 | Butanoic acid | < 0.0 | Butanoic acid | 1.6 |
| Heptanal | 1.0 | Heptanal | 0.2 | Heptanal | 1.7 |
| Butanal | 1.1 | Butanal | 0.1 | Butanal | 1.8 |
| Octanal | 0.8 | Octanal | 0.2 | Octanal | 1.5 |
| Methyl cyclopentane | 2.0 | Methyl cyclopentane | 0.1 | Methyl cyclopentane | 0.3 |
| Nonatal | 0.7 | Nonatal | 0.5 | Nonatal | 1.7 |
| Toluene | 2.0 | Toluene | 1.0 | Toluene | 0.4 |
| *n*-Propanol | 1.4 | *n*-Propanol | 41.3 | *n*-Propanol | 2.3 |
| 2-Butanol | 0.5 | 2-Butanol | 1.3 | 2-Butanol | 0.5 |
| 4-Ethyl-phenol | 0.1 | 4-Ethyl-phenol | < 0.0 | 4-Ethyl-phenol | 0.3 |
| 1-Pentanol | 0.1 | 1-Pentanol | < 0.0 | 1-Pentanol | < 0.0 |
| Dimethyl trisulphide | 0.2 | Dimethyl trisulphide | < 0.0 | Dimethyl trisulphide | 0.2 |
| 2-Methyl-propenoic acid methyl ester | 10.8 | 2-Methyl-propenoic acid methyl ester | < 0.0 | 2-Methyl-propenoic acid methyl ester | < 0.0 |
| 2-Methyl-propenoic acid | < 0.0 | 2-Methyl-propenoic acid | 0.2 | 2-Methyl-propenoic acid | < 0.0 |
| 2-Methyl-hexanoic acid | < 0.0 | 2-Methyl-hexanoic acid | 0.1 | 2-Methyl-hexanoic acid | < 0.0 |
| Propyl propenoic ester | < 0.0 | Propyl propenoic ester | 0.2 | Propyl propenoic ester | < 0.0 |
| Indole | 1.5 | Indole | 0.1 | Indole | < 0.0 |
| Benzaldehyde | 0.3 | Benzaldehyde | 0.1 | Benzaldehyde | < 0.0 |
| *o*-Xylene | 0.3 | *o*-Xylene | < 0.0 | *o*-Xylene | < 0.0 |
| Decanal | < 0.0 | Decanal | 0.2 | Decanal | < 0.0 |
| n-Propyl acetate | < 0.0 | n-Propyl acetate | 4.8 | n-Propyl acetate | < 0.0 |
| Benzene | < 0.0 | Benzene | 0.3 | Benzene | 0.2 |
| Menthanol | < 0.0 | Menthanol | 1.7 | Menthanol | < 0.0 |
| Dimethyl sulfone | < 0.0 | Dimethyl sulfone | < 0.0 | Dimethyl sulfone | 0.2 |
| Ethanol | < 0.0 | Ethanol | 0.1 | Ethanol | < 0.0 |
| D-limonene | < 0.0 | D-limonene | 0.1 | D-limonene | < 0.0 |
| Total | 100 | Total | 100 | Total | 100 |

***Particulate matter***

It may be expected that housing systems with litter (solid manure) produce greater dust emissions than livestock housing without litter (slurry), because bedding material such as straw consists of loose material, which is easily made airborne by disturbance (Hinz et al., 2000). Takai et al. (1998) found greater inhalable dust concentrations in English dairy cow housing with litter than in German dairy cubicle houses with slurry-based systems. The calculated emission rates for PM differed, too. However, PM emissions have also been found to be 50 % less in a deep-litter system because the dust is incorporated into the bed and held there by the moisture. Animal activity does not cause as much suspension of material if the litter is moist (CIGR Working Group, 1995).

Emissions of PM occur from both housed and free-range livestock. However, the lack of available emissions measurements for free-range livestock means that the development of EFs has focused on housed livestock.

### *A1.2.2 Reported emissions*

### *Ammonia*

$NH_3$ emission from cattle on grassland is highly variable and most of the emission originates from urine patches (Laubach et al. 2012, 2013, Nichols et al. 2018).

Increasing addition of N in fertilizer to the grassland will contribute to increased protein concentration in the grass. Hence the intake of N will increase thereby increasing N excretion. Most of this increase is in the urine (Jarvis et al. 1989; Bussink 1992). Balancing N intake to the protein intake requirements of the grazing livestock reduces N excretion and $NH_3$ emission (Voglmeier et al. 2018).

$NH_3$ emissions increase with increasing soil moisture content (Bussink 1992). Air temperature, wind speed, global radiation and rainfall all influence emissions (Voglmeier et al. 2018; Bell et al. 2017).

Ammonia volatilization from sows on grassland was related to the amount of feed given to the sows, incident solar radiation and air temperature during measuring periods and rain 1-2 days before measurements (Sommer et al. 2001). The influencing parameters are to those reported for cattle on grassland and are related to more N in urine due to increased protein given in feed, and weather parameters increasing the $NH_3$ emission potential.

**Table A1.3 Ammonia emission factors grazing emissions. Emissions as a % of total N excreted**

| Manure type | Number of studies | Weighted mean | Standard deviation |
|---|---|---|---|
| Dairy cattle | 8 | 9 | 6.9 |

No peer reviewed publications were identified of $NH_3$ arising from pastures grazed by beef cattle. Therefore the EF derived for dairy cattle has been used for beef cattle as well.

### *Non-methane volatile organic compounds*

An exhaustive list of over 130 volatile compounds identified in livestock buildings housing cattle, pigs and poultry was compiled by O'Neill and Phillips (1992) in a literature review. More recent compilations by Schiffman et al. (2001) and Blunden et al. (2005) identified over 200 VOCs in air from buildings housing pigs confirming most of the previous emission profiles. Ni et al. (2012) identified over 500 compounds. The compounds most frequently reported in these investigations, which were heavily biased towards piggeries, were *p*-cresol, VFAs and phenol. Concentrations of these compounds in the atmosphere display wide variations, e.g. the concentration of *p*-cresol varies from $4.6 \times 10^{-6}$ to 0.04 mg $m^{-3}$ and the concentration of phenol varies from $2.5 \times 10^{-6}$ to 0.001 mg $m^{--3}$. The alcohols ethanol and methanol have been reported as the dominant emissions from buildings housing dairy cattle and sheep (Ngwabie et al., 2005; US EPA, 2012), and these vastly exceed VFA and *p*-cresol abundances. VOCs are also known to be adsorbed to airborne PM (Bottcher, 2001; Oehrl et al., 2001; Razote et al., 2004; Cai et al. 2006b), thus representing an additional emission pathway and odour nuisance.

A major attempt to quantify the NMVOC emissions from livestock housing and manure stores was made in the NAEM study that covered 16 locations in the USA with dairy cattle, sow and pig finishing facilities, as well as egg layer and broiler farms (US EPA, 2012). The measurements were made over two consecutive years from 2007 to 2009. NMVOC measurements were made with both canister sampling combined with mass spectrometry and NMHC.

The estimated NMVOC EF is based on an average emission measured in the NAEM study for dairy cows, sows, layers and broilers. If both NMVOC and NMHC were measured, an average of the two values was used. NMHCs are converted to NMVOCs by multiplying with the mass fraction of the most common NMVOCs compared with NMHCs. The emissions from the NAEM study are converted to European standards with a conversion of MJ feed intake data and VS excretion, which corresponds to data in the 2006 IPCC Guidelines (IPCC, 2006). Measurements in the NAEM study indicate that the emission depends on temperature and ventilation rates. However, because of the significant variation of the measured emission, the data are not robust enough to introduce a climate-dependent EF for the EMEP area.

For cattle, emissions from only dairy housing were measured. These emissions include those from silage feeding in the building, enteric fermentation, flatus and from manure stored inside the building. A conversion to 'other cattle' has been made according to the relative intake of energy (in MJ). For all other livestock, the conversions are based on the differences in excreted VSs to allow for differences in productivity.

Measured emissions from dairy housing in the NAEM study include emissions from silage, which is a major source. The major emissions from silage are ethanol and VFAs. There is a large uncertainty with regard to the fraction that is derived from the silage. Alanis et al. (2008) found, for a Californian dairy farm, that the total mixed rations (TMRs) (silage feed) were responsible for approximately 68 % of estimated VFA emissions. Chung et al. (2010) found that 93–98 % of the emissions that contributed to $O_3$ formation from six dairies came from the feed. In the distribution of the EFs for emissions from silage on the feeding table and emissions from other sources in the building (enteric, other feeding stuff and manure store inside the building), values of 85 % from the silage and 15 % from other sources are used. This factor will affect the emission estimate from farms not using silage for feeding. In the NAEM study, propanol accounted for up to 50 % of the emission from cattle, poultry and pig housing (Table A1.2). Chung et al. (2010) found only alcohol emissions from the feed (ethanol and propanol) and nothing from the flushing lane, bedding, open lots or lagoons. This gives rise to questions regarding the origin of the high propanol measurements in the NEAM study, as poultry and pigs are not normally fed with silage.

The methodology for silage stores is based on measured distribution between silage stores and buildings (Alanis et al., 2008; Chung et al., 2010), combined with a temperature correction to account for European temperatures (Alanis et al., 2010; El-Mashad et al., 2010; Hafner et al., 2010). Emissions were measured under warmer conditions (20°C) than the European average. A correction factor from 20°C to 10°C was therefore made that was equal to 25 % of the emissions from silage on the feeding table.

The NMVOC measurements in the NAEM study from lagoons are difficult to translate to manures stored in slurry tanks. Therefore, the fraction of NMVOC emissions between housing and storage was based on the same fraction as for the $NH_3$ emission. This relationship is documented by, among others, Hobbs et al. (2004), Amon et al. (2007) and Feilberg et al. (2010). The same methodology is used to calculate the NMVOC emissions resulting from the application of manure by using the fraction of $NH_3$ emissions resulting from application compared with emissions from buildings. However, it should be mentioned that if national $NH_3$ data are used, this will not necessarily reduce the emission estimate, as low $NH_3$ emission rates based on low N feeding will not reduce the primary dry matter in feed and the excreted volatile substances, which are the primary source for NMVOCs. For the Tier 1 EFs, the distribution in Table 3.9 was used. The use of national $NH_3$ emission estimates is strongly recommended. Rumsey et al. (2012) found, when upscaling the emission from pigs in North Carolina, USA, that housing was responsible for 68.8–100 % of the total emissions. This large proportion may be unlikely under European conditions, as the use of large aerated lagoons is not common practice in Europe.

NMVOC emissions from grazing animals are assumed to be small as there is little or no silage feeding and no manure to store. However a small amount will be emitted from enteric fermentation and from flatus. The estimation of emissions from grazing animals is based on Shaw et al. (2007) who measured reactive organic gas (ROG) emissions from lactating and non-lactating dairy cows for two subsequent days in an emission chamber. Based on the feed composition it is assumed that the feeding was without silage, although alfalfa was included. It is assumed that alfalfa was in the form of hay. The estimated ROG is assumed to be equivalent to NMVOC.

### *A1.2.3 Controls*

#### *Ammonia*

The adoption of techniques to reduce $NH_3$ emissions needs to be taken into account when estimating national $NH_3$ emissions. This is most easily done using a Tier 3 approach, in which the EF for the appropriate stage of manure management can be reduced by the proportion of $NH_3$ emission achieved by the abatement technique. The average reductions in $NH_3$ emissions that can be achieved by recognised abatement techniques can be found in UNECE (2007).

Information will also be needed on the proportions of livestock housed in reduced-emission buildings, the proportion of manures stored under cover and the proportion of manures applied by reduced-emission techniques.

#### *Nitric oxide*

Meijide et al. (2007) reported a reduction in NO emissions of c. 80 % when the nitrification inhibitor dicyandiamide (DCD) was added to pig slurry before application to land, although unabated emissions were only 0.07 % of N applied.

#### *Non-methane volatile organic compounds*

Further examples of abatement techniques include the provision of only small amounts of feed on the feeding table; the use of high-quality feed with a high digestibility, which reduces the amount of substrate for NMVOC formation; and the immediate removal of urine and manure from cubicles for cattle, the fast removal of slurry for pigs, belt drying of manure inside the poultry houses for laying hens and the limited stirring of manure in manure stores. Systems already described for reducing $NH_3$ emissions from storage facilities, such as natural and artificial floating crust and floating mats, give some odour reduction because of the reduction in the emissions of NMVOCs (Mannebeck, 1986; Zahn et al. 2001; Bicudo et al., 2004; Blanes-Vidal et al., 2009).

#### *Particulate matter*

Techniques have been investigated to reduce concentrations of airborne dust in livestock housing. Measures such as wet feeding, including fat additives in feed, oil and/or water sprinkling, are some examples of techniques that prevent excessive dust generation within the building.

End-of-pipe technologies are also available to reduce PM emissions significantly, in particular filters, cyclones, electrostatic precipitators, wet scrubbers and biological waste air purification systems. Although many of these are currently considered too expensive, technically unreliable or insufficiently user friendly to be widely adopted by agriculture, air scrubbers are considered to be category 1 abatement options by the UNECE (2007).

Shelterbelts (the planting of, for example, trees and shrubs as screens around the building to remove airborne PM) may also reduce the dispersal of PM emitted from buildings to a certain extent.

When applicable abatement techniques become available, the methodology will be developed to allow the calculation of the corresponding PM emissions.

## A1.3 Methods

### *A1.3.1 Tier 1 approach*

***Particulate matter***

In order to develop EFs expressed per AAP, transformation factors are needed for the conversion of livestock units into AAP. In addition, inhalable and respirable dust concentrations have to be transformed into the corresponding PM concentrations. However, the resulting 'correction factors' have to be used with care, because the representativeness of these factors is poorly understood. As a consequence, this Tier 1 methodology is considered very uncertain.

**Table A1.4 Measured dust emissions (all data except horses: Takai et al., 1998; horses: Seedorf and Hartung, 2001)**

| Code | Livestock category | Housing type | Emissions | |
|---|---|---|---|---|
| | | | ID, mg $LU^{-1}$ $h^{-1}$ | RD, mg $LU^{-1}$ $h^{-1}$ |
| 3B1a | Dairy cattle | slurry | 172.5 | 28.5 |
| | | solid | 89.3 | 28.0 |
| 3B1b | Non-dairy cattle (all other cattle except calves). | slurry | 113.0 | 13.7 |
| | | solid | 85.5 | 16.0 |
| 3B1b | Non-dairy cattle (calves) | slurry | 127.5 | 19.5 |
| | | solid | 132.0 | 27.3 |
| 3B4e | Horses | solid | 448.5 | 47.5 |
| | | solid ([a]) | 55.0 | n.a. |

Notes:

([a])Wood shavings.

h, Animal head; ID, inhalable dust; LU, livestock unit; n.a., not available; RD, respirable dust.

Sources: Takai et al., 1998 (all data except horses); Seedorf and Hartung, 2001 (data on horses).

In order to get mean emissions per animal head, mean values of these data have to be divided by the average weight of the animals in the corresponding category. Livestock unit (LU) is here defined as a unit used to compare or aggregate numbers of different species or categories, and is equivalent to 500 kg live weight. The weights used are given in Table A1.5. These values have also been used for the conversion to EF per animal in other studies.

**Table A1.5 Conventional livestock units and weights of livestock on which the N excretion estimates in Table 3.9 were based**

| Code | Livestock type | Weight of animal used for $N_{ex}$ estimate (kg) |
|---|---|---|
| 3B1a | Dairy cattle | 600 |
| 3B1b | Non-dairy cattle (all other cattle) | 340 |
| 3B1b | Non-dairy cattle (calves) | 150 |
| 3B2 | Sheep | 50 |
| 3B3 | 'Swine' (finishing pigs)[b] | 65 |
| 3B3 | 'Swine' (piglets to 8 kg) | 20 |
| 3B3 | 'Swine' (sows) | 225 |
| 3B4a | Buffalo | 700 |
| 3B4d | Goats | 50 |
| 3B4e | Horses | 500 |
| 3B4f | Mules and assess | 350 |
| 3B4gi | Laying hens | 2.2 |
| 3B4gii | Broilers | 1.0 |
| 3B4giii | Turkeys | 6.8 |
| 3B4giv | Other poultry (ducks) | 2.0 |
| 3B4giv | Other poultry (geese) | 3.5 |
| 3B4h | Other animals (fur animals) | NA |

[b] From 8 kg until slaughter

In the cases for which PM EFs are not directly available, the quantities of inhalable and respirable dust have to be transformed into quantities of $PM_{10}$ and $PM_{2.5}$. Transformation factors for cattle were derived from a 24-hour PM monitoring survey that was performed in a cubicle house with dairy cows and calves, housed on a slatted floor and a solid floor with straw. The 1-day survey was conducted with an optical particle counter, which recorded the mass concentrations of total dust, $PM_{10}$ and $PM_{2.5}$. The result of this investigation was used to calculate the conversion factor for $PM_{10}$ (Seedorf and Hartung, 2001), while the conversion factor for $PM_{2.5}$ was determined later (Seedorf and Hartung, personal communication). For horses, a transformation factor similar to that for cattle was assumed. Overall, the real quantitative relationships between dust fractions have to be verified in future. Nevertheless, for a very first estimate, some of these transformation factors are compiled in Table A1.6.

**Table A1.6 Transformation factors for the conversion of inhalable dust into $PM_{10}$ and $PM_{2.5}$**

| **Code** | **Livestock type** | **Transformation factor for $PM_{10}$, kg $PM_{10}$ kg (ID)$^{-1}$** | **Transformation factor for $PM_{2.5}$, kg $PM_{2.5}$ kg (ID)$^{-1}$** |
|---|---|---|---|
| 3B1a | Dairy cattle | 0.46 (a) | 0.30 (b) |
| 3B1b | Other cattle | 0.46 (a) | 0.30 (b) |
| 3B4e | Horses (c) | 0.46 (a) | 0.30 (b) |

Note:

(a)The same conversion factor for horses is assumed as for cattle (Seedorf and Hartung, 2001).

(b)Seedorf (personal communication).

(c)The transformation factor for $PM_{2.5}$ relates to respiratory dust and not inhalable dust.

ID, inhalable dust.

The resulting EFs in kg animal$^{-1}$ a$^{-1}$ are listed in Table A1.7.

**Table A1.7 EFs for inhalable dust, respirable dust, $PM_{10}$ and $PM_{2.5}$**

| Code | Livestock category | Housing type | Animal weight, kg animal$^{-1}$ | Conversion factor, LU animal$^{-1}$ | EFs | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | ID, kg AAP$^{-1}$ a$^{-1}$ | RD, kg AAP$^{-1}$ a$^{-1}$ | $PM_{10}$, kg AAP$^{-1}$ a$^{-1}$ | $PM_{2.5}$, kg AAP$^{-1}$ a$^{-1}$ |
| 3B1a | Dairy cattle | Slurry | 600 | 1.2 | 1.81 | 0.30 | 0.83 | 0.54 |
| | | Solid | 600 | 1.2 | 0.94 | 0.29 | 0.43 | 0.28 |
| 3B1b | Beef cattle | Slurry | 350 | 0.7 | 0.69 | 0.08 | 0.32 | 0.21 |
| | | Solid | 350 | 0.7 | 0.52 | 0.10 | 0.24 | 0.16 |
| 3B1b | Calves | Slurry | 150 | 0.3 | 0.34 | 0.05 | 0.15 | 0.10 |
| | | Solid | 150 | 0.3 | 0.35 | 0.07 | 0.16 | 0.10 |
| 3B2 | Sheep | Solid | | | 0.14 | | 0.056 | 0.017 |
| 3B4a | Buffalos | Slurry | 700 | 1.4 | 2.12 | 0.35 | 0.97 | 0.63 |
| | | Solid | 700 | 1.4 | 1.10 | 0.34 | 0.50 | 0.33 |
| 3B4d | Goats | Solid | | | 0.139 | | 0.056 | 0.017 |
| 3B4e | Horses | Solid ([a]) | 500 | 1.0 | 0.48 | | 0.22 | 0.14 |
| 3B4f | Mules and asses | Solid | 350 | 0.7 | 0.34 | | 0.16 | 0.10 |
| 3B4giv | Ducks | Solid | 2 | 0.004 | 0.14 | 0.018 | 0.14 | 0.018 |
| 3B4giv | Geese | Solid | 3.5 | 0.007 | 0.24 | 0.032 | 0.24 | 0.032 |
| 3B4h | Fur animals | Solid | | | | | 0.0081 | 0.0042 |

Notes:

([a]) Wood shavings.

ID, inhalable dust; n.a. not available; RD, respirable dust.

For cattle, the Tier 1 EFs are based on the solid/liquid distribution of the livestock manure management systems (LMMSs). The LMMS solid/liquid distribution in the EU-27 for dairy cattle is 49/51 and for non-dairy cattle is 59/41, according to EU reporting to the UNFCCC in 2011. Based on these values, the LMMS solid/liquid distribution is assumed to 50/50 for dairy cattle and 60/40 for other cattle.

The EFs given in Table A1.8 are mainly of a similar order of magnitude to those used in the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model for livestock operations accessible at http://www.iiasa.ac.at/). However, for cattle, there is a clear discrepancy between the values presented in Table 3.5 and GAINS EFs. This may be caused by the use of different measurement techniques. More work is required to understand the observed differences, and the EFs presented here and in the GAINS model should therefore be used with caution.

### *A1.3.2 Tier 2 technology-specific approach*

#### *Ammonia*

Tables A1.8 to A1.11 give the EFs used in the national inventories of the EAGER group. The Tier 2 EFs used in this chapter were derived as averages of these national EFs. References to the national models are given in the footnotes for each table.

The EFs used in the Tier 2 mass-flow approach to calculate emissions of $N_2O$-N during manure storage are based on the default IPCC EFs and are given in Table A1.8. The IPCC EFs are expressed as proportions of total N at excretion. In order to convert from the IPCC EF to EFs as proportions of TAN in manures entering storage, the IPCC EF is divided by the proportion of TAN in manure-N entering storage, hence the link between the IPCC default EF and those used in the guidebook methodology will not be immediately apparent.

**Table A1.8 Derivation of default Tier 2 EF for direct $N_2O$ emissions from manure management. Annex Table A1. explains how the manure storage types referred to here relate to those used by IPCC**

| Storage system | IPCC default EF, kg $N_2O$-N (kg $N_{ex}$)$^{-1}$ | Proportion of TAN in manure at storage ($^a$) | EF, kg $N_2O$-N (kg TAN entering store)$^{-1}$ |
|---|---|---|---|
| Cattle slurry without natural crust | 0 | 0.50 | 0 |
| Cattle slurry with natural crust | 0.005 | 0.50 | 0.01 |
| Pig slurry without natural crust | 0 | 0.65 | 0 |
| Cattle manure heaps, and solid | 0.005 | 0.25 | 0.02 |
| Pig manure heaps, and solid | 0.005 | 0.40 | 0.01 |
| Sheep and goat manure heaps, and solid | 0.005 | 0.30 | 0.02 |
| Horses, mules and asses manure heaps, and solid | 0.005 | 0.25 | 0.02 |
| Layer manure heaps, solid | 0.001 | 0.55 | 0.002 |
| Broiler manure heaps, solid | 0.001 | 0.65 | 0.002 |
| Turkey and duck manure heaps, solid | 0.001 | 0.60 | 0.002 |
| Goose manure heaps, solid | 0.001 | 0.60 | 0.002 |
| Buffalo manure heaps, solid | 0.005 | 0.25 | 0.02 |

Note:**($^a$)**Based on output from the European Agricultural Gaseous Emissions Inventory Researchers (EAGER) network (http://www.eager.ch/).

**Ammonia emissions from livestock housing**

There is a wide range of housing categories in Europe and $NH_3$ emission from livestock housing is much affected by floor design, manure removal, cleaning etc. In the Tier 2 $NH_3$ emission methodology the calculation scheme is simplified in recognition that data on production systems is often sparse and little may be known about manure management. Therefore, it has been decided to provide EFs for only the main categories of livestock production and manure management systems. Each of these categories, therefore, cover a wide range of EFs, that will vary among countries and should have an influence on the calculated national emission inventories.

Floor design may affect $NH_3$ emission. Emission from fattening pig houses is affected by the ratio of slatted floor to concrete floor area (Sommer et al. 2006), and by the floor opening area (Philippe et al. 2016). Emission is related to excretion pattern, which is affected by positioning of feeders and drinkers, and behavior of pigs as related to age and temperature (Aarnink et al. 2006). So the use of EFs for very few categories of e.g. livestock housing design and manure management systems cover a wide range of EFs that should be related to pen and floor design.

Management of the manure may also affect emission from similar housing designs i.e. emission from a solid floor with scrapers increases $NH_3$ emission compared with emission from a perforated floor, and solid floor with flushing system may reduce the emission (Baldini, et al. 2016). Further, the study of Baldini, et al. (2016) showed that emissions varied between feeding alleys and cubicles.

In studies of $NH_3$ emission from livestock housing the results are given as the measured emission from the building per time unit, in emission per animal, emission per livestock unit (LU), a percentage of TAN or total N in excreta. The definition of animal and LU may vary among countries (institute), a LU may be defined as the production of a livestock equivalent to 500 kg live weight (Philippe et al. 2011a ) or as 100 kg N in the outlet from a manure store (Kai et al. 2008). Measurement of N and TAN in excretion is also complicated due to the heterogeneity of the manure and the right timing of sampling. The precision of calculated total N and TAN excretion is affected by the model available, information about feed uptake, breed etc. Gilhespy et al. (2009) calculated the emission from cattle housed in deep litter houses as a percentage of TAN excreted, and noted that the range of emission was as wide as 5.4 – 20%, because the excretion model did not account for animal size and variation in feed added, so when housing a large breed they underestimated TAN excretion. Using standard excretion data may be problematic, because N excretion varies much among countries (Hou et al. 2016), due to differences in feed intake and diet formulation, which significantly affects manure composition and $NH_3$ emission (Dourmad et al. 1999; Edouard et al. 2016).

In most publications, the emission is given as g $NH_3$ per animal per day or per LU per day, and may vary much due to differences in housing design, management and feeding practice. The publications are often not providing enough information to assess N or TAN in excreta. So even if the influence of feeding may be reduced to some extend by assessing the emission as a percentage of TAN or total N, then this estimate may unfortunately not be very precise. The variation due to differences in pen and barn design may in future be reduced by developing models that include emission as related to surface structures and managements of these.

Determining gaseous EFs from livestock buildings requires long-term measurements with high precision and reliable instruments. Emissions should be measured in different seasons to observe their seasonality and diurnal variation (Rzeźnik and Mielcarek 2016). Only measurements carried out for several seasons in different housing systems make it possible to calculate valid EFs covering an average of the annual emission should be used to estimate emissions from other buildings.

***Calculation method***

The EF for a category was determined by using measured emission estimates from peer reviewed journals. The supplementary material lists emission data in a range of units as given in the papers; $NH_3$ emitted as a percentage of TAN or total N excreted, g N per animal per day, g N per animal per hour, g N LU per year etc. It has been decided to give the emission as a percentage of TAN excreted per year. Consequently it has been necessary to convert data to this format. If data are given:

1. in % of TAN excreted then data is used unchanged.
2. for poultry emissions expressed as the % of N-total excreted may be converted to TAN by calculating the fraction in excreta that is TAN or in a short time will be transformed to TAN (i.e. uric acid)
3. in relation to number of head of livestock then the national value of N excretion per head is used to obtain N excretion.
4. In relation to LU then the number of animals are calculated based on the annual average weight of an animal in that livestock class and excretion is estimated using national excretion data.

The excretion data from Velthof et al. (2015) were used to calculate the amount of Total N excreted per head of livestock when no excretion data were provided for the livestock category in the publication. The rationale for using these data was that they report excretion calculated with the NIR model from the IPCC guidelines, this model calculate N-excretion as the difference in N intake and N retention in livestock and livestock products. To calculate the TAN excretion the ratio of TAN to total – N excreted in EMEP/EEA air pollutant emission inventory guidebook (2016) is used.

If the emission is given per LU and average weight of animals in the livestock category are not given, so that number of animals per LU cannot be calculated then the EUROSTAT definition of number of animals per LU is used (Annex 2).

If emission is given in heat producing units (HPU) then it is assumed that one HPU equal to animals heat production of 1000 W at environmental temperature of 20C; For a dairy cow of 600 kg that produce about 30-35L/ milk that will be ca. 1.45 HPU per LU.

**Cattle litter systems**

The data suggest greater $NH_3$-N emission from dairy on deep litter than from beef, which is plausible because dairy cattle are bigger than beef cattle, require more feed and hence excrete more N. Secondly the data suggest that deep litter systems emit more $NH_3$-N than from tied stalls which is also plausible because the emitting surface area in a tied stall is smaller (Webb et al. 2012).

**Poultry manure**

Poultry manure differs from other livestock manure because the TAN in poultry manure originates mainly from decomposed uric acid in the droppings. Hydrolysis of uric acid is slow and is affected by storage conditions, so the concentration of TAN is often more variable than for other manures (Kroodsma et al., 1988). The design of poultry houses and manure management affect transformation of uric acid and thus to a great extent $NH_3$ emissions (Groot Koerkamp, 1994). Increase in excretion from broilers causes the emission to increase significantly over time so emission from broilers slaughtered after 30 d is much lower than if they are slaughtered after more than 30 days (Pereira 2017).

**Table A1.9 Ammonia emission factors for buildings housing livestock as % of TAN excreted**

| Manure type | Number of studies | Weighted mean | Standard deviation |
|---|---|---|---|
| All cattle slurry | 14 | 24 | 14.7 |
| Dairy cattle tied | 5 | 9 | 6.9 |
| All cattle solid | 9 | 8 | 5.7 |
| Sows and litters slurry | 5 | 35 | 9.1 |
| Sows and litters solid | 5 | 24 | 10.4 |
| Finishing pigs slurry | 19 | 27 | 12.1 |
| Finishing pigs solid | 12 | 23 | 14.7 |
| Layer manure | 7 | 20 | 12.9 |
| Broiler manure | 7 | 21 | 10.0 |

**Table A1.10 Examples of EFs derived from EFs used in national inventories used for individual stages of manure management, expressed as percentages of TAN [a) Housing]**

| Livestock category | Housing type | Denmark | Germany | Netherlands | Switzerland | United Kingdom |
|---|---|---|---|---|---|---|
| 3B2 Sheep | Solid | 25.0 | 22.0 | 11.0 | | 21.6 |
| 3B4a Buffaloes | Solid | | 19.7 ($^a$) | | | |
| 3B4d Goats | Solid | 25.0 | 22.0 | 11.0 | | 21.6 |
| 3B4e Horses | Solid | 25.0 | 22.0 | | | |
| 3B4e Mules and asses | Solid | 25.0 | 22.0 ($^b$) | | | |
| 3B4giii Turkeys | Litter | 35.7 | 52.9 | 32.1 | | 19.2 |
| 3B4giv Ducks | Litter | 35.7 | 11.4 | 32.1 | | 17.5 |
| 3B4giv Geese | Litter | 35.7 | 57.0 | | | |
| 3B4h Fur animals | NA | 30.0 | 27.0 | | | |

($^a$)In the German inventory, buffaloes are included in the category 'Other cattle'.

($^b$)In the German inventory, mules and asses are included in the category 'Horses'.

**Ammonia emissions during manure storage**

The transfer of $NH_3$ from stored manure to the atmosphere is not as complex as the transfer of $NH_3$ from livestock housing. The release of $NH_3$ from stored liquid manure or livestock slurry is primarily of a physical or chemical nature, because the anaerobic microbial transformation is relatively slow. Little TAN is produced during storage and the concentration of organic acids is relatively constant.

In contrast, the $NH_3$ emissions from stored solid manure are related to microbial activity in the manure, which is influenced by air flow through the manure heap.

*Liquid manure*

Ammonia emissions are larger from stored pig slurry than from cattle slurry, due to a greater TAN concentration. Furthermore, emissions tend to be twice as large from slurry that has been fermented in a biogas plant than from untreated slurry, because fermented slurry has a higher pH and TAN content. Ammonia emissions from slurry in open tanks, silos and lagoons range from 0.78 to 2.33 kg $NH_3$-N $m^{-2}$ $a^{-1}$.

*Solid manure*

A newly created heap acts as a source of $NH_3$ for a few weeks, until the moisture content falls sufficiently to halt decomposition or until all the volatile N has been emitted as $NH_3$ or oxidised N, or has been converted into organic N. After the initial days with high emissions from heaps with available TAN then emissions are relatively small and turning of the heaps after more than one month storage does not increase emission rates (Ariaga et al. 2017).

In stores of solid manure with little straw or a high water content (>50-60%), the diffusion rate of $O_2$ is low and composting nearly absent (Webb et al., 2012; Bernal et al. 2017). $NH_3$ emissions therefore occur exclusively from the outer surface of the stack. $NH_3$ emission is, therefore, reduced by compacting the manure heaps and by avoiding addition of manure to the surface after establishing the heap (Webb et al. 2012). The addition of fresh manure to the surface of the stack creates a new outer surface from which emissions can occur. Each fresh addition of manure creates a new pulse of $NH_3$ emissions.

In contrast, if self-heating (composting) occurs, then warm air moves through the heap and the potential for $NH_3$ emissions is large. The decomposition of organic matter results in rapid mineralisation of organic N and an increase in pH due to a reduced concentration of organic acids, which together with high temperatures leads to high concentrations of $NH_3$ (aq) and to rapid and substantial emissions.

Losses of 25-30% of the total-N in stored pig manure and cattle deep litter have been recorded, although losses of only 1-10% have also been measured. The lessser losses may be related to stores of cattle FYM with only a small amount of straw and a high density, which do not decompose aerobically. Consequently, $NH_3$ emission from cattle FYM is generally less than from heaps of pig FYM, which often will be aerobic and start to decompose aerobically. Further, losses may also be reduced due to the leaching of TAN by rainwater (Webb et al., 2012).

*Calculation of emission factors*

In most publications the annual emission of $NH_3$ from liquid manure stores is given as g $NH_3$ $m^{-2}$ $a^{-1}$. This is a meaningful unit, because emission from stored slurry is related to the surface area, in addition to the effect of surface TAN concentration, surface pH, weather etc. The EFs presented here have been related to a 3 m storage depth and an average of TAN concentration in the studies from where data were collated.

The emission from stored livestock and poultry solid manure is much affected by transformation of N between the organic and inorganic fraction. This is reflected in that the EFs related to TAN in the studies reviewed may vary from a few % to more than 200%. This large variation is related to the carbon to N ratio (C:N) and to degradability of the organic N in the manure. In the calculation of $NH_3$ emission from solid manure the EF is related to TAN in the manure at the beginning of the storage period, which is not an ideal solution, because transformation between organic N and TAN depends on a range of factors – carbon to N (C:N), resilience of organic matter, oxygen content – porosity, size of heap, cover, turning etc. (Bernal et al. 2017). In future EFs should be related to the most important parameters in the transformation of organic N to TAN.

Data from measurements of emission using small dynamic chambers in a laboratory have been omitted from the assessment of EFs, irrespective that they give useful information about emission as related to treatments (Perazzolo et al. 2015; Owusu-Twum et al. 2017). The data have been used to assess the effect of the treatments.

The EFs for storage emissions were derived from values published in peer-reviewed literature. Emission from slurry stores is given as a percentage of TAN. Where total emissions appear to be greater then 100% of TAN the data have been omitted from the calculations. Mean emissions, expressed as a % of TAN entering the store were weighted by the number of stores in each study. Table A1.11 provides the number of studies reported for each type of manure together with the weighted mean and standard deviation of the mean.

**Table A1.11 Ammonia emission factors for stored manure as % of TAN entering store**

| Manure type | Number of studies | Weighted mean | Standard deviation |
|---|---|---|---|
| All cattle slurry | 5 | 25 | 11.2 |
| | | | |
| Dairy cattle solid | 8 | 7 | 5.4 |
| Beef cattle solid | 8 | 38 | 35.5 |
| All cattle solid | 16 | 28 | 32.8 |
| | | | |
| Pig slurry | 4 | 11 | 6.9 |
| Pig solid | 63 | 63 | 64.3 |
| | | | |
| Layer manure | 3 | 5 | 4.5 |
| Broiler manure | 6 | 27 | 25.1 |

Due to the absence of any studies of emissions from stored beef slurry and the essential similarity between slurry produced by dairy and beef animals, the EF for stored cattle slurry is used for all cattle slurry.

Although the means for dairy and beef solid storage emissions were very different we considered solid manure produced by dairy and beef animals to be essentially the same and hence a single EF was derived for stored cattle solid manure.

**Table A1.12 Examples of EFs derived from EFs used in national inventories used for individual stages of manure management, expressed as percentages of TAN [b) Storage]**

| Livestock category | Housing type | Denmark | Germany | Netherlands | Switzerland | United Kingdom |
|---|---|---|---|---|---|---|
| 3B2 Sheep | Solid | 10.0 | 60.0 | 5.0 | | 34.8 |
| 3B4a Buffaloes | Solid | | 16.7 | | | 40.0 |
| 3B4d Goats | Solid | 10.0 | 60.0 | 5.0 | | 34.8 |
| 3B4e Horses | Solid | 10.0 | 60.0 | | | 11.8 |
| 3B4f Mules and asses | Solid | 10.0 | 60.0 | | | 11.8 |
| 3B4giii Turkeys | Litter | 25.0 | 6.5 | 45.0 | | 17.8 |
| 3B4giv Ducks | Litter | 25.0 | 6.5 | 45.0 | | 17.8 |
| 3B4giv Geese | Litter | 25.0 | 6.5 | | | |
| 3B4h Fur animals | NA | 8.5 | | | | |

**Table A1.16 Ammonia emission factors for solid manure applied to soil**

| Manure type | Number of studies | Weighted mean | Standard deviation |
|---|---|---|---|
| Dairy cattle solid | 11 | 63 | 21.2 |
| Beef cattle solid | 12 | 66 | 23.3 |
| All cattle solid | 23 | 65 | 20.8 |
| Pig solid | 13 | 36 | 26.1 |
| Layer manure | 13 | 41 | 23.2 |
| Broiler manure | 8 | 37 | 22.8 |

There was a reasonable number of studies reporting $NH_3$ emissions following the application of both dairy and beef solid manure applied to land. However, in view of the essential similarity between slurry produced by dairy and beef animals, the data for emissions from solid manure from dairy and beef cattle were combined to give a single EF for all solid cattle manure.

**Table A1.17 Examples of EFs derived from nationa inventories used for individual stages of manure management, expressed as percentages of TAN [c) Spreading]**

| Livestock category | Housing type | Denmark | Germany | Netherlands | Switzerland | United Kingdom |
|---|---|---|---|---|---|---|
| 3B2 Sheep | Solid | | 90.0 | 100.0 | | 81.0 |
| 3B4a Buffaloes | Solid | | 55.0 | | | |
| 3B4d Goats | Solid | | 90.0 | 100.0 | | 81.0 |
| 3B4e Horses | Solid | | 90.0 | | | |
| 3B4f Mules and asses | Solid | | 90.0 | | | |
| 3B4giii Turkeys | Litter | | 90.0 | 55.0 | | 63.0 |
| 3B4giv Ducks | Litter | | 90.0 | 55.0 | | 63.0 |
| 3B4giv Geese | Litter | | 90.0 | | | |
| 3B4h Fur animals | NA | | | | | |

## A1.6 Tier 3 emission modelling and use of facility data

Other factors, in addition to those listed in section 2.2.1, which influence $NH_3$ emissions and which may be taken into account using Tier 3 methodologies, are listed below:

- the amount and N content of feed consumed;
- the efficiency of the conversion of N in feed to N in meat, milk and eggs and, hence, the amount of N deposited in excreta;
- climatic conditions in the building (e.g. temperature and humidity) and the ventilation system;
- the storage system of the manure outside the building, i.e. open or covered slurry tank, loose or packed heap of solid manure;
- any treatment applied to the manure such as aeration, separation or composting.

The way in which manure is managed greatly influences emissions of $NH_3$, since the processes that govern the emission of N species differ among solid, liquid (slurry) and FYM. The addition of litter with a large carbon to N ratio to livestock excreta will promote the immobilisation of TAN in organic N and hence reduce $NH_3$ emissions. The nature of FYM varies considerably; if it is open and porous, nitrification may take place, whereas if the manure becomes compact, denitrification may occur. Both processes mean that N can be lost as NO, $N_2O$ and $N_2$. It is therefore necessary to specify the type of manure produced and to account for variations in manure management.

$NH_3$ emissions from livestock manures during housing and storage and as a result of field application also depend on:

- the temperature and ventilation rates within buildings;
- the size of the soiled surface;
- contact of the manure with ambient air (or cover on the manure store);
- the properties of the manure, including viscosity, TAN content, C content and pH;
- soil properties such as pH, cation exchange capacity, calcium content, water content, buffer capacity and porosity;
- the meteorological conditions including precipitation, solar radiation, temperature, humidity and wind speed;
- the method and rate of application of livestock manures, including, for arable land, the time between application and incorporation, and the method of incorporation;
- the height and density of any crop present.

***Particulate matter***

The mass flows of emitted particles are governed by the following parameters (examples in parentheses), thus causing uncertainties in terms of predicted emissions (Seedorf and Hartung, 2001):

- building design and operation:
    - ventilation (forced vs naturally ventilated);
    - climate (temperature and relative humidity);
    - type of floor (partly or fully slatted);
    - geometry and positions of inlets and outlets (re-entrainment of deposited particles caused by turbulence above the surfaces within the building);
- livestock bedding:
    - type of material (straw or wood shavings);
    - physical properties of the material;
    - quantity and quality (e.g. straw, chopped straw, wood shavings, sawdust, peat, sand, use of de-dusted bedding materials, mixtures of different materials, litter moisture, supplementation with de-moisturing agents, used mass of bedding material per animal);
- livestock management:
    - animal activity (species, circadian rhythms, young vs adult animals, caged vs aviary systems);
    - time in housing (whole year vs seasonal housing);
    - feeding systems (dry vs wet, automatic vs manual, feed storage conditions);

  - manure systems (liquid vs solid, removal and storage, manure drying on conveyor belts).
  - Type of housed livestock (poultry vs mammals).

### *Record of updates*

**Table A1.15 Summary of updates to calculation methodologies and EFs made during the 2019 revision of this chapter**

| Emission type | Tier 1 Methodology | Tier 1 EFs | Tier 2 Methodology | Tier 2 EFs |
|---|---|---|---|---|
| $NH_3$ | Not updated | Updated to provide Tier 1 EFs based on the new Tier 2 EFs | Updated to take account of manures used for biogas production | Updated |
| NO | Not updated | Not updated | NA | NA |
| NMVOC | Not updated | Not updated | Updated | Updated |
| PM | Not updated | Not updated | NA | NA |

NA, not applicable.

# Annex references

Aarnink, A. J. A., Cahn, T. T. and Mroz, Z., 1997, ‘Reduction of ammonia volatilization by housing and feeding in fattening piggeries’, in: Voermans, J. A. M. and Monteney, G. J. (eds), *Ammonia and odour emission from animal production facilities*, Vinkeloord, the Netherlands 283–291.

Aarnink, A. J. A., Schrama, J. W., Heetkamp, M. J. W., Stefanowska, J. and Huynh, T. T. T., 2006, 'Temperature and body weight affect fouling of pig pens', *Journal of Livestock Science*, (84) 2224–2231.

Amon, B., Kryvoruchko, V., Fröhlich, M., Amon, T., Pöllinger, A., Mösenbacher, I. and Hausleiter, A., 2007, ‘Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage’, *Livestock Science*, (112) 199–207.

Arriaga H., Viguria M., Lopez D. M. and Merino P., 2017, 'Ammonia and greenhouse gases losses from mechanically turned cattle manure windrows: A regional composting network', *Journal of Environmental Management*, (203) 557-563.

Asteraki, E. J., Matthews, R. A. and Pain, B. F., 1997, 'Ammonia emissions from beef cattle bedded on straw', in: Voermans, J. A. M. and Monteny, G. J., (eds.), *Ammonia and odour control from animal production facilities*, Nederlandse Vereniging Techniek Landbouw, Rosmalen, the Netherlands, 343–347.

Baldini, C., Borgonovo, F., Gardoni, D. and Guarino, M., 2016, 'Comparison among $NH_3$ and GHGs emissive patterns from different housing solutions of dairy farms', *Atmospheric Environment*, (141) 60-66.

Bell, M., Flechard, C., Fauvel, Y., Häni, C., Sintermann, J., Jocher, M., Menzi, H., Hensen, A. and Neftel, A., 2017, 'Ammonia emissions from a grazed field estimated by miniDOAS measurements and inverse dispersion modelling', *Atmospheric Measurement Technology*, (10) 1875–1892.

Bernal, P. M., Sommer, S. G., Chadwick, D., Qing, C., Guoxue, L. and Michel, F. C., 2017, 'Current Approaches and Future Trends in Compost Quality Criteria for Agronomic, Environmental, and Human Health Benefits', in: Sparks, D. L., (ed), *Advances in Agronomy*, (144) Burlington, Academic Press, 143-233.

Bicudo, J. R., Clanton, C. J., Schmidt, D. R., Powers, W., Jacobson, L. D. and Tengman, C. L., 2004, ‘Geotextile covers to reduce odour and gas emissions from swine manure storage ponds’, *Applied Engineering in Agriculture*, (20) 65–75.

Blanes-Vidal, V., Hansen, M. N. and Sousa, P., 2009, ‘Reduction of odor and odorant emissions from slurry stores by means of straw covers’, *Journal of Environmental Quality*, (38) 1518–1527.

Blunden, J., Aneja, V. P. and Lonneman, W. A., 2005, ‘Characterization of non-methane volatile organic compounds at swine facilities in eastern North Carolina’, *Atmospheric Environment*, (39) 6707–6718.

Bottcher, R., 2001, ‘An environmental nuisance: Odor concentrated and transported by dust’, *Chemical Sensors*, (263) 327–331.

Bussink, D. W., 1992, 'Ammonia volatilization from grassland receiving nitrogen fertilizer and rotationally grazed by dairy cattle'. *Nutrient Cycling in Agroecosystems*, (33) 257-265.

Cahn, T. T., Aarnink, A. J. A., Schulte, J. B., Sutton, A., Langhout, D. J. and Verstegen, M. W. A., 1998, ‘Dietary protein affects nitrogen excretion and ammonia emission from slurry of growing finishing pigs’, *Livestock Production Science*, (56) 181–191.

Cai, L., Koziel, J. A., Davis, J., Lo, Y-C. and Xin, H., 2006a, ‘Characterization of volatile organic compounds and odors by in-vivo sampling of beef cattle rumen gas, by solid-phase microextraction and gas chromatography–mass spectrometry-olfactometry’, *Analytical and Bioanalytical Chemistry*, (386) 1791–1802.

Cai, L., Koziel, J. A., Davis, J., Lo, Y-C. and Hoff, S. J., 2006b, ‘Characterization of volatile organic compounds and odorants associated with swine barn particulate matter using solid-phase microextraction and gas chromatography–mass spectrometry-olfactometry’, *Journal of Chromatography A*, (1102) 60–72.

Chambers, B., Smith, K., and van der Weerden, T., 1997, '$NH_3$ emissions following the land spreading of solid manures', in, Jarvis, S. and Pain, B., (eds.), *Gaseous Nitrogen Emissions from Grasslands*, CAB International, Wallingford, 275-280.

CIGR Working Group, 1995, ‘Aerial environment in animal housing — Concentration in and emission from farm buildings’, 3rd Report, CIGR Working Group No 13: Climatization and Environmental Control in Animal Housing (www-med-physik.vu-wien.ac.at/bm/cigr/reports/rep3_sum.htm).

Dourmad, J. Y., Guingand, N., Latimier, P. and Seve, B., 1999, 'Nitrogen and phosphorus consumption, utilisation and losses in pig production: France', *Livestock Production Science*, (58) 199–211.

Edouard, N., Hassouna, M., Robin, P., et al., 2016, 'Low degradable protein supply to increase nitrogen efficiency in lactating dairy cows and reduce environmental impacts at barn level', *Livestock*, (10) 212-220.

Elliott-Martin, R. J., Mottram, T. T., Gardner, J. W., Hobbs, P. J. and Bartlett, P. N., 1997, ‘Preliminary investigation of breath sampling as a monitor of health in dairy cattle’, *Journal of Agricultural Engineering Research*, (67) 267–275.

El-Mashad, H. M., Zhang, R., Rumsey, T., Hafner, S., Montes, F., Rotz, C. A., Arteaga, V., Zhao, Y. and Mitloehner, F.M., 2010, ‘A mass transfer model of ethanol emission from thin layers of corn silage’, *Transactions of the American Society of Agricultural and Biological Engineers,* (536) 1903–1909.

Ettalla, T. and Kreula, M., 1979, ‘Studies on the nitrogen compounds of the faeces of dairy cows fed urea as the sole or partial source of nitrogen’, in: Kreula, M. (ed.), *Report on metabolism and milk production of cows on protein-free feed, with urea and ammonium salts as the sole source of nitrogen, and an urea-rich, low protein feed*, Biochemical Research Institute, Helsinki, 309–321.

Faassen van, H. G. and Van Dijk, H., 1987, ‘Manure as a source of nitrogen and phosphorus in soils’. In: Van Der Meer, H. G., Unwin, R. J., Van Dijk, T. A. and Ennik, G. C. (eds), *Animal manure on grassland and fodder crops. Fertilizer or waste? Developments in plant and soil science*.

Gilhespy, S. L., Webb, J., Chadwick, D. R., Misselbrook, T. H., Kay, R., Camp, V., Retter, A. L. and Bason, A., 2009, 'Will additional straw bedding in buildings housing cattle and pigs reduce ammonia emissions?', *Biosystem Engineering*, (102) 180-189.

Groenwold, J. G., Oudendag, D., Luesink, H. H., Cotteleer, G. and Vrolijk, H., 2002, ‘Het Mest- en Ammoniakmodel’. LEI, Den Haag, Rapport 8.2.2003 (in Dutch).

Groot Koerkamp, P. W. G., 1994, ‘Review on emissions of ammonia from housing systems for laying hens in relation to sources, processes, building design and manure handling’, *Journal of Agricultural Engineering Research*, (59) 73–87.

Haenel, H.-D., Rösemann, C., Dämmgen, U., Freibauer, A,, Döring, U., Wulf, S., Eurich-Menden, B., Döhler, H., Schreiner, C. and Osterburg, B., 2016, Calculations of gaseous and particulate emissions from German agriculture 1990 - 2014. Report on methods and data (RMD) Submission 2016. Braunschweig : Johann Heinrich von Thünen Inst, 408 p, Thünen Rep 39.

Hafner, S. D., Montes, F., Rotz, C. A. and Mitloehner, F., 2010, Ethanol emission from loose corn silage and exposed silage particles. *Atmospheric Environment*, (44) 4172–4180.

Hansen, M. N., Birkmose, T., Mortensen, B. and Skaaning, K., 2004, Miljøeffekter af bioforgasning og separering af gylle. Grøn viden, Markbrug nr. 296, Ministeriet for Fødevare, Landbrug og Fiskeri. Pp 6.

Hinz, T., Sonnenberg, H., Linke, S., Schilf, J. and Hartung, J., 2000, ‘Staubminderung durch Befeuchten des Strohs beim Einstreuen eines Rinderstalles’, *Landtechnik*, (55) 298–299.

Hou, Y., Bai, Z., Lesschen, J. P., Staritsky, I. G., Sikirica, N., Ma, L., Velthof, G. L., Oenema, O., 2016, 'Feed use and nitrogen excretion of livestock in EU-27', *Agriculture, Ecosystems & Environment*, 218, 232-244.

James, T., Meyer, D., Esparza, E., Depeters, E. J. and Perez-Monti H., 1999, ‘Effects of dietary nitrogen manipulation on ammonia volatilization from manure from Holstein heifers’, *Journal of Dairy Science*, (82) 2430–2439.

Jarvis, S. C., Hatch, D. J., Roberts, D. H., 1989, 'The effects of grassland management on nitrogen losses from grazed swards through ammonia volatilization; the relationship to excretal N returns from cattle', *Journal of Agricultural Science*, (112) 205–216.

Kai, P., Pedersen, P., Jensen, J. E., Hansen, M. N. and Sommer, S. G., 2008. 'A whole-farm assessment of the efficacy of slurry acidification in reducing ammonia emissions', *European Journal of Agronomy*, (28) 148–154.

Kay, R. M. and Lee, P. A., 1997, ‘Ammonia emissions from pig buildings and characteristics of slurry produced by pigs offered low crude protein diets’. In: Voermans, J. A. M. and Monteny, G. J. (eds), *Ammonia and odour emission from animal production facilities*. Vinkeloord, the Netherlands, 253–259.

Karlsson, S. and Salomon, E., 2002, 'Deep litter manure to spring cereals – Manure properties and $NH_3$ emissions'. Poster presented at the 10th International Conference of the FAO European System of Cooperative Research Networks in Agriculture (ESCORENA) – Recycling of Agricultural, Municipal and Industrial Residues in Agriculture Network (RAMIRAN), Strbske Pleso, High Tatras, Slovak Republic, May 14-18 2002. Report (paper) in Conference Proceedings.

Kellems, R. O., Miner, J. R. and Church, D. C., 1979, ‘Effect of ration, waste composition and length of storage on the volatilization of ammonia, hydrogen sulphide and odor from cattle waste’, *Journal of Animal Science*, (48) 436–445.

Kroodsma, W., Scholtens, R. and Huis in ’t Veld, J. W. H., 1988, 'Ammonia emission from poultry housing systems, in: Nielsen, V. C., Voorburg, J. H. and L’Hermite, P. (eds), *Volatile Emissions from Livestock Farming and Sewage Operations*, Elsevier Applied Science, London and New York, 152–161.

Latimier, P. and Dourmad, J., 1993, ‘Effect of three protein feeding strategies for growing-finishing pigs on growth performance and nitrogen output in the slurry and in the air’. 6 In: Verstegen, M. W. A., Den Harlog, L. A., van Kempen, J. G. M. and Metz, J. H. M. (eds), *Nitrogen flow in pig production and environmental consequences*. EAAP publication No 69, Pudox, Wageningen, the Netherlands, 242–24.

Laubach, J., Taghizadeh-Toosi, A., Gibbs, S. J., Sherlock, R. R., Kelliher, F. M. and Grover S. P. P., 2013, ‘Ammonia emissions from cattle urine and dung excreted on pasture’, *Biogeosciences*, (10) 327–338.

Laubach, J., Taghizadeh-Toosi, A., Sherlock, R. R. and Kelliher, F. M., 2012, 'Measuring and modelling ammonia emissions from a regular pattern of cattle urine patches', *Agriculture and Forest Meteorology*, (156) 1-17.

Mackie, R. I., Stroot, P. G. and Varel, V. H., 1998, ‘Biochemical identification and biological origin of key odor components in livestock waste’, *Journal of Animal Science*, (76) 1331–1342.

Mannebeck, H., 1986, ‘Covering manure storing tanks to control odour’, in: *Odour prevention and control of organic sludge and livestock farming*, Elsevier, London, 188–193.

Meijide, A., Díez, J. A., Sánchez-Martín, L., López-Fernández, S. and Vallejo, A., 2007, ‘Nitrogen oxide emissions from an irrigated maize crop amended with treated pig slurries and composts in a Mediterranean climate’, *Agriculture, Ecosystems and Environment*, (121) 383–394.

Montes, F., Hafner, S. D, Rotz, C. A., and Mitloehner, F. M., 2010, ‘Temperature and air velocity effects on ethanol emission from corn silage with the characteristics of an exposed silo face’, *Atmospheric Environment*, (44) 1987–1995.

Moss, A. R., Jouany, J-P. and Newbold, J., 2000, ‘Methane production by ruminants: its contribution to global warming’, *Annuals de Zootechnie*, (49) 231–253.

Ngwabie, N. M., Custer, T. G., Schade, G. W., Linke, S. and Hinz, T., 2005, ‘Mixing ratio measurements and flux estimates of volatile organic compounds VOC) from a cowshed with conventional manure treatment indicate significant emissions to the atmosphere’, *Geophysical Research Abstracts*, (7) 01175.

Ngwabie, N. M., Schade, G. W., Custer, T. G., Linke, S. and Hinz, T., 2008, ‘Abundances and Flux Estimates of Volatile Organic Compounds from a Dairy Cowshed in Germany’. *Journal of Environmental Quality,* (37) 565–573.

Ni, J.-Q., Robarge, W. P., Xiao, C., and Heber, A. J., 2012, ‘Volatile organic compounds at swine facilities: A critical review’, *Chemosphere*, (89) 769–788.

Nichols, K. L., Del, Grosso S. J., Derner, J. D., Follett, R. F., Archibeque, S. L., Delgado, J. A. and Paustian, K. H., 2018, 'Nitrous Oxide and Ammonia Emissions from Cattle Excreta on Shortgrass Steppe', *Journal of Environmental Quality*, (47) 419-426.

Oehrl, L. L., Keener, K. M., Bottcher, R. W., Munilla, R. D. and Connelly, K. M., 2001, ‘Characterization of odor components from swine housing dust using gas chromatography’, *Applied Engineering Agriculture*, (175) 659–661.

O’Neill, D. H. and Phillips, V. R., 1992, ‘A review of the control of odour nuisance from livestock buildings: Part 3, Properties of the odorous substances which have been identified in livestock wastes or in the air around them’, *Journal of Agricultural Engineering Research*, (53) 23–50.

Owusu-Twum, M. Y., Polastre, A., Subedi, R., Santos, S. S., Ferreira, L. M. M., Coutinho, J. and Trindade, H., 2017, 'Gaseous emissions and modification of slurry composition during storage and after field application: Effect of slurry additives and mechanical separation', *Journal of Environmental Management*, (200) 416-422.

Parker, D. B., Caraway, E.A., Rhoades, M. B., Cole, N. A., Todd, R. W. and Casey, K.D., 2010, ‘Effect of wind tunnel air velocity on VOC flux from standard solutions and CAFP Manure/Wastewater’, *Transactions of the American Society of Agricultural and Biological Engineers*, (53) 831–845.

Parker, D. B., Gilley, J., Woodbury, B., Kim, K-H., Galvin, G., Bartelt-Hunt, S. L., Li, X. and Snow, D. D., 2012, ‘Odorous VOC emission following land application of swine manure slurry’, *Atmospheric Environment*, (66) 91–100.

Patni, N. K. and Jui, P. Y., 1985, ‘Volatile fatty acids in stored dairy-cattle slurry’, *Agricultural Wastes*, (13) 159–178.

Paul, J. W., Dinn, N. E., Kannagara, T. and Fisher L. J., 1998, ‘Protein content in dairy cattle diets affects ammonia losses and fertilizer nitrogen value’, *Journal of Environmental Quality*, (27) 528–534.

Perazzolo, F., Mattachini, G., Tambone, F., Misselbrook, T. and Provolo, G., 2015, 'Effect of mechanical separation on emissions during storage of two anaerobically codigested animal slurries', *Agriculture, Ecosystems & Environment*, (207) 1-9.

Petersen, S. O., Sommer, S. G., Aaes O. and Søergaard, K., 1998, ‘Ammonia losses from urine and dung of grazing cattle: Effect of N intake’, *Atmospheric Environment*, (32) 295–300.

Philippe, F.-X., Cabaraux, J.F. and Nicks, B. 2011, 'Ammonia emissions from pig houses: Influencing factors and mitigation techniques', *Agriculture, Ecosystems and Environment*, (141) 245–260.

Philippe, F.-X., Laitat, M., Wavreille J. and Nicks B. 2016, 'Floor slat openings impact ammonia and greenhouse gas emissions associated with group-housed gestating sows, *Livestock*, (10) 2027-2033.

Razote, E. B., Maghirang, R. G., Seitz, L. M. and Jeon, I. J., 2004, ‘Characterization of volatile organic compounds on airborne dust in a swine finishing barn’, *Transactions of the American Society of Agricultural Engineers*, (474) 1231–1238.

Regione Emilia-Romagna, 2007, 'Tecniche innovative per la misura e Migliori Tecniche Disponibili (MTD) per la riduzione delle emissioni nell’allevamento', [Innovative techniques for measurements and Best Available Techniques (BAT) for the reduction of the emissions in the livestock farms, Final technical report], Rendicontazione tecnica finale, a cura di C.R.P.A., Internal report.

Rumsey, I. C., Aneja, V. P. and Lonneman, W. A., 2012, ‘Characterizing non-methane volatile organic compounds emissions from a swine concentrated animal feeding operation’. *Atmospheric Environment*, (47) 348–357.

Rzeźnik W. and Mielcarek P., 2016, 'Greenhouse Gases and Ammonia Emission Factors from Livestock Buildings for Pigs and Dairy Cows', *Polish Journal of Environmental Studies*, (25) 1813-1821.

Sagoo, E., Williams, J. R., Chambers, B. J., Boyles, L. O., Matthews, R. and Chadwick, D. R., 2007, 'Integrated management practices to minimise losses and maximise the crop nitrogen value of broiler litter'. *Biosystems Engineering*, (97), 512-519.

Schiffman, S., Bennett, J. and Raymer, J., 2001, ‘Quantification of odors and odorants from swine operations in North Carolina’, *Agriculture and Forest Meteorology*, (1083) 213–240.

Smits, M. C. J., Valk, H., Elzing, A. and Keen, A., 1995, ‘Effect of protein nutrition on ammonia emission from a cubicle house for dairy cattle’, *Livestock Production Science*, (44) 147–156.

Sommer, S. G., Søgaard, H. T., Møller, H. B. and Morsing, S., 2001, 'Ammonia volatilization from sows on grassland' *Atmospheric Environment*, (35) 2023-2032.

Sommer, S. G., Zhang, G. Q., Bannink, A., Chadwick, D., Hutchings, N. J., Misselbrook, T., Menzi, H., Ni, Ji-Qin, Oenema, O., Webb, J. and Monteny, G.-J. 2006, 'Algorithms determining ammonia emission from livestock houses and manure stores', *Advances in Agronomy* (89) 261 - 335.

Spinhirne, J. P., Koziel, J. A. and Chirase, N. K., 2003, ‘A device for non-invasive on-site sampling of cattle breath with solid-phase microextraction’, *Biosystems Engineering*, (84) 239–246.

Spinhirne, J. P., Koziel, J. A. and Chirase, N. K., 2004, ‘Sampling and analysis of volatile organic compounds in bovine breath by solid-phase microextraction and gas chromatography–mass spectrometry’, *Journal of Chromatography A*, (1025) 63–69.

Trabue, S., Scoggin, K., Li, H., Burns, R., Xin, H. and Hatfield, J., 2010, ‘Speciation of volatile organic compounds from a poultry production’, *Atmospheric Environment*, (44) 3538–3546.

UNECE, 2007, ‘Control techniques for preventing and abating emissions of ammonia. Executive Body for the Convention on Long-Range Transboundary Air Pollution. Working Group on Strategies’, United Nations Economic Commission for Europe

(https://www.unece.org/fileadmin/DAM/env/documents/2007/eb/wg5/WGSR40/ece.eb.air.wg.5.2007.13.e.pdf), accessed 30 September 2016.

Velthof, G. L., Hou, Y. and Oenema, O., 2015, 'Nitrogen excretion factors of livestock in the European Union: a review', Journal of the Science of Food and Agriculture, (95) 3004-3014.

Voglmeier, K., Jocher, M., Häni, C. and Ammann, C., 2018, 'Ammonia emission measurements of an intensively grazed pasture', *Biogeosciences*, (15) 4593-4608.

Webb, J., Thorman, R. E., Fernanda-Aller, M. and Jackson, D. R., 2014, 'Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types', Atmospheric Environment, (82) 280-287.

Whitehead, D. C., Lockyer, D. R. and Raistrick, N., 1989, ‘Volatilization of ammonia from urea applied to soil: influence of hippuric acid and other constituents of livestock urine’, *Soil Biology and Biochemistry*, (21) 803–808.

Whitehead, D. C., 1990, ‘Atmospheric ammonia in relation to grassland agriculture and livestock production’, *Soil Use and Management*, (6) 63–65.

Zahn, J. A., Hatfield, J. L., Do, Y. S., DiSpirito, A. A., Laird, D. A. and Pfeiffer, R. L., 1997, ‘Characterization of volatile organic emissions and wastes from a swine production facility’, *Journal of Environmental Quality*, (26) 1687–1696.

Zahn, J. A., Tung, A. E., Roberts, B. A. and Hatfield, J. L., 2001, ‘Abatement of ammonia and hydrogen sulphide emissions from a swine lagoon using a polymer biocover’, *Journal of the Air and Waste Management Association*, (51) 562–573.