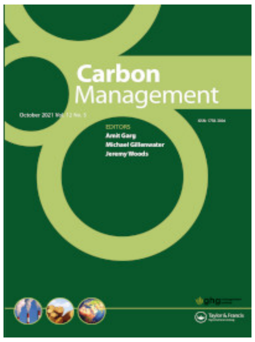
Guidance on the conversion of gaseous emission units to standardized emission factors and recommendations for data reporting

J. Webb, T. van der Weerden, Mélynda Hassouna, B. Amon



Carbon Management

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcmt20

Guidance on the conversion of gaseous emission units to standardized emission factors and recommendations for data reporting

J. Webb, T. J. van der Weerden, M. Hassouna & B. Amon

CARBON MANAGEMENT
https://doi.org/10.1080/17583004.2021.1995502

Taylor & Francis
Taylor & Francis Group

Guidance on the conversion of gaseous emission units to standardized emission factors and recommendations for data reporting

J. Webb[a], T. J. van der Weerden[b], M. Hassouna[c] and B. Amon[d,e]

[a]Faculty of Science and Engineering, University of Wolverhampton, Wolverhampton, UK; [b]Invermay Agricultural Centre, AgResearch Ltd, Mosgiel, New Zealand; [c]AgroEcosystems, INRAE, UMR SAS, Rennes cedex, France; [d]Department of Technology Assessment and Substance Cycles, Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V, Potsdam, Germany; [e]Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, Zielona Góra, Poland

ABSTRACT
Emissions of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) from livestock production may be measured for different reasons and in consequence reported in a wide range of units. For the purpose of compiling national inventories of emissions of those gases, emissions from buildings and stores usually need to be expressed per animal or as a proportion of nitrogen (N) (NH_3 and N_2O) or volatile solids (VS) (CH_4) excreted or stored. Much of the published data on gaseous emissions from livestock production is not reported in units that can be readily used for inventory compilation. This paper provides guidance for researchers wishing to convert a wide range of emission units into emission factors (EFs) and opens up opportunities for increased use of published data. We developed our methodology using reported emissions from housing and storage systems compiled from studies for the DATAMAN database so that we could convert reported emissions into agreed EFs referred to as 'required EFs' (RqEFs). Required EFs were either derived using data reported in the associated publication or estimated, using default data (e.g. annual N excretion by a particular type of livestock).
The approach greatly increased the number of RqEFs. For example, the number of RqEFs of N_2O-N from livestock buildings as a proportion of excreted N increased from 16 to 326, while the number of N_2O RqEFs from manure stores as a proportion of stored N increased from 126 to 353.
For two subsets of NH_3-N emissions from livestock buildings and from slurry stores there were very good correlations between emissions estimated using the methodology we developed and reported emissions ($R^2 = 0.97$ and 0.97, respectively). We include a list of recommended information for inclusion in publications reporting emissions that will enable other workers to utilize this methodology.

KEYWORDS
Methane; nitrous oxide; greenhouse gases; ammonia; emission inventories; emission factor

Introduction

Livestock production has been estimated to produce between 8 and 18% of global emissions of greenhouse gases (GHG) [1]. These emissions, mainly as methane (CH_4) and nitrous oxide (N_2O), arise from enteric fermentation and from the application of nitrogen (N) fertilizer and livestock manures to land. Agriculture is the largest source of ammonia (NH_3) in the atmosphere, accounting for *c*. 80% of total emissions [2].

In order to meet international agreements to limit these emissions there has been an increasing global effort to quantify them, identify and better understand the key biotic and abiotic factors leading to these emissions and to improve national reporting [e.g. 3]. The preparation of emission inventories is an essential part of achieving these goals for three reasons: to identify the main sources of emissions in order to formulate approaches to make the most effective reductions in emissions; to provide annual updates of total emissions in order to assess compliance with agreed commitments; to provide data for models of dispersion and the impacts of the emissions [2].

When reporting the results of an individual experiment to determine the impact of changes in inputs or management practices on emissions from agricultural activities, the units in which the measurements are reported are, arguably, arbitrary. Depending on the objective of individual studies, what is important is to report the outcomes so that the impact of housing, manure treatments, changes in inputs or management practices, etc. can be reliably quantified. However, when attempting to quantify absolute emissions from

CONTACT J. Webb j01webb@aol.com Faculty of Science and Engineering, University of Wolverhampton, Wolverhampton, UK

different sources and to compare results obtained from different studies, it is helpful to have emissions reported in an agreed format. For reporting national emission inventories it is necessary to have emission units that can be related to available activity data and are consistent with national emission inventory methodologies.

When compiling emission inventories, gaseous emissions from livestock housing may most simply be expressed as g of the gas, or for nitrogenous gases, the g of N in the gas, per animal. This means that for a livestock class, such as mature dairy cows, the measured emission can be readily put in the context of other reported measurements from buildings housing dairy cows and contribute to overall 'emission factors' (EFs) used in inventory compilation, e.g. [2]. Moreover, livestock numbers will usually be known to a reasonable degree of accuracy. However, expressing emissions per animal does not allow easy comparison of emissions among different livestock classes. It is of no surprise, given the different sizes of the animals, that emissions of NH_3 are greater from a dairy cow than from a laying hen. For this reason, the convention has been adopted, and widely followed, of expressing emissions as g of N or pollutant per 500 kg of animal live weight; the 'livestock unit' (LU). However, while this unit is frequently used and meaningful it takes no account of factors such as: floor area per animal; presence and type of bedding; diet; animal performance and other management factors that interact with the characteristics of the animal to influence total emissions [2]. It was partly for this reason that expressing NH_3 emissions as a % of N or total ammoniacal-N (TAN) excreted by a class of livestock was adopted since diet and hence N excretion are major drivers of the emissions of N gases (e.g. [7]). Similarly, CH_4 emissions are often expressed as % of volatile solids (VS) excreted by a class of livestock [e.g. 4]. Expressing NH_3 and nitrous oxide (N_2O) emissions as a percentage of N or TAN excreted or CH_4 as VS excreted also facilitates calculation of emissions throughout the sequence of manure management. By doing so, the impact of changing emissions at an early stage, such as housing, on emissions at later stages, such as storage, can be estimated enabling the creation not only of inventories but also cost curves for abatement measures [e.g. 5,6].

Emissions from manure stores are most often reported per unit area of store (liquid manures) or per weight or volume of solid manures in the store. However, for mass-flow models expression per unit of N, TAN or VS is also necessary [e.g. 2,7].

Recently, the DATAMAN project was created to build publicly available global databases of CH_4, N_2O and NH_3 emissions (plus relevant activity and ancillary data) relating to livestock housing, storage and field application of manure (including excreta deposited during grazing) [8, 9]. The overall aim of the DATAMAN project is to provide researchers and policy makers alike with the most up-to-date knowledge on methods for managing GHG and NH_3 emissions from manure. This work has been extended through a new project called "Mitigating Emissions from Livestock Systems (MELS[1])" to widen the breadth of the databases and include the development of farm-scale decision support tools. The databases being constructed will allow statistical analysis of global datasets, resulting in revised EFs and improved understanding of key drivers influencing emissions of NH_3, N_2O and CH_4 from livestock and manure management systems. A database of field-based emissions has been publicly released recently [9]. However, the database for livestock housing and manure storage emissions currently contains a large number of observations (*c.* 2700 measurements from buildings and *c.* 1900 from stores) employing a plethora of units. For example, emissions of NH_3 from buildings housing livestock were reported in 65 different units and emissions of CH_4 from manure stores in 47 different units. The majority of housing and storage data contained within the DATAMAN databases were sourced from the ELFE database [10].

In some cases the different units were essentially of the same basis, but used different orders of magnitude for either the emission or the time over which the emission was reported, e.g. kg, g, mg, µg, ng of emission per second, minute, hour, day or year. However, emissions were also reported in units less easy to convert to the preferred units listed above, as data required for the conversion were not always available from the paper reporting the emissions.

The purposes of this study were firstly, to provide a methodology that increases the use of the wealth of published emission data, secondly to provide guidance for researchers wishing to convert a wide range of emission units into EFs that align with IPCC and UNECE national inventory reporting; thirdly, to apply the methods developed to data held in the DATAMAN database. Developing approaches for converting emissions reported in units not commonly used in inventory preparation into standard EFs used in inventories (per animal, per LU or as a proportion of N or VS excreted) has the potential to markedly increase the data available for statistical analysis. An increase in the number of observations available for statistical analysis provides greater opportunity to determine key drivers of emissions, disaggregate emission factor (EF) values according to different livestock types, housing systems, storage methods and identify practices aimed at mitigating emissions. This paper reports the methodology used to make these conversions and an assessment of how successful the work was. The EFs derived from the resulting harmonization of emissions data will be reported separately [11].

Methods

Emissions from livestock housing

In order to provide guidance for the conversion of emission units into revised EF units, we have used livestock housing and manure storage data currently being collated for the DataMan database as the source data for our study. The desired EF units for this database are:

- NH_3 as kg NH_3-N per kg of N excreted by the livestock in the building during the time the measurements were made.
- NH_3 as g NH_3-N per 500 kg livestock unit (LU) per day in the building during the time the measurements were made.
- NH_3 as g NH_3-N per animal per day in the building during the time the measurements were made.
- N_2O as kg N_2O-N per kg of N excreted by the livestock in the building.
- N_2O as g N_2O-N per 500 kg LU per day in the building.
- N_2O as g N_2O-N per animal per day in the building.
- CH_4 as kg CH_4 per kg of VS excreted by the livestock in the building.
- CH_4 as g CH_4 per 500 kg LU per day in the building.
- CH_4 as g CH_4 per animal per day in the building.

These units will be referred to as 'required EFs' (RqEFs).

Table 1 lists the different units used to express emissions of NH_3, N_2O and CH_4 collated in the databases and information on whether the conversion of these units to RqEFs was done on the basis of the RqEFs being supplied, derived or estimated. There is no systematic distinction between the 'supplied' and 'derived' approaches; whether a RqEF could be 'derived' or 'supplied' depended upon the availability of the necessary data within the spreadsheet. These terms are explained below.

Supplied EFs

Supplied EFs were those in which the reported emission unit could be converted to a RqEF by a simple numeric adjustment. For example, emissions of NH_3-N and N_2O-N reported as % of N excreted by the livestock have been converted to kg N per kg N excreted by multiplying the reported EF by 10. Where emissions have been reported as NH_3 or N_2O the conversion has been made to NH_3-N and N_2O-N. Where emissions of CH_4 have been expressed as % of VS or as CH_4-C, these have been also converted to kg kg^{-1} VS and kg CH_4 respectively and regarded as 'supplied'.

Derived EFs

Conversions that required the use of data from elsewhere in the database, e.g. from emission per animal to emission per LU, requiring data on livestock weights and or numbers from within the database, have been considered as 'derived'.

Conversion from emissions per animal to emission per livestock unit. Where emissions per animal have been supplied, conversion to emissions per LU was carried out by dividing the supplied emission by the reported weight of the individual animals.

For livestock such as finishing pigs, for which the animal weight will have increased during the measurement period, the mean weight was not always reported. In such cases it could often be calculated as the mean of the reported start and end weights over the measurement period, or by adding the daily weight gain multiplied by the number of days emissions were measured to the start weight.

For a few observations, a range of measurements was provided, either of emissions or animal weights. In such cases the mid point was taken as the average emission or weight. In a very few cases animal weights were given as '$< x$' or '$> x$'. In these cases the weight was taken as '$x - 1$' kg and '$x + 1$' kg, respectively. This was considered the best option as it was consistent with the value

Table 1. List of the units used to report emissions from buildings housing livestock and the data needed to convert them to the required EFs. hpu = heat producing unit; LW = live weight; lwg = live weight gain.

Units used in the papers examined	Data needed to convert units to g LU^{-1} d^{-1}, g $animal^{-1}$ d^{-1} or kg kg^{-1} N (for NH_3 and N_2O) and kg kg^{-1} VS (for CH_4)
Supplied	
NH_3	
g NH_3-N LU^{-1} d^{-1}	None
g NH_3-N LU^{-1} h^{-1}	None
g NH_3 LU^{-1} d^{-1}	None
g NH_3 LU^{-1} h^{-1}	None
kg NH_3 LU^{-1} yr^{-1}	None
g NH_3-N $animal^{-1}$ d^{-1}	None
g NH_3-N $animal^{-1}$ h^{-1}	None
g NH_3 $animal^{-1}$ d^{-1}	None
g NH_3 $animal^{-1}$ h^{-1}	None
mg NH_3-N $animal^{-1}$ h^{-1}	None
mg NH_3 $animal^{-1}$ h^{-1}	None
mg NH_3 $animal^{-1}$ d^{-1}	None
kg NH_3 $animal^{-1}$ yr^{-1}	None
kg NH_3 animal $place^{-1}$ yr^{-1}	None
% N excreted	None
N_2O	
g N_2O LU^{-1} d^{-1}	None
g N_2O LU^{-1} h^{-1}	None
mg N_2O LU^{-1} d^{-1}	None
mg N_2O LU^{-1} h^{-1}	None
μg N_2O LU^{-1} s^{-1}	None
g N_2O kg LW^{-1} d^{-1}	None
kg N_2O LU^{-1} yr^{-1}	None
g N_2O-N $animal^{-1}$ d^{-1}	None
g N_2O-N $animal^{-1}$ h^{-1}	None
mg N_2O-N $animal^{-1}$ h^{-1}	None
kg N_2O-N $animal^{-1}$ yr^{-1}	None
g N_2O $animal^{-1}$ d^{-1}	None
g N_2Oanimal^{-1} h^{-1}	None
g N_2O $animal^{-1}$ yr^{-1}	None
mg N_2O $animal^{-1}$ d^{-1}	None
mg N_2O $animal^{-1}$ h^{-1}	None
μg N_2O $animal^{-1}$ s^{-1}	None
kg N_2O animal $place^{-1}$ yr^{-1}	None
% N excreted	None
CH_4	
g CH_4 LU^{-1} d^{-1}	None
g CH_4 LU^{-1} h^{-1}	None
mg CH_4 LU^{-1} s^{-1}	None
kg CH_4 LU^{-1} yr^{-1}	None
g CH_4 kg LW^{-1} d^{-1}	None
g CH_4 $animal^{-1}$ d^{-1}	None
g CH_4 $animal^{-1}$ h^{-1}	None
mg CH_4 $animal^{-1}$ d^{-1}	None
mg CH_4 $animal^{-1}$ h^{-1}	None
mg CH_4 $animal^{-1}$ s^{-1}	None
kg CH_4 $animal^{-1}$ yr^{-1}	None
kg CH_4 $animal^{-1}$ d^{-1}	None
kg CH_4 animal $place^{-1}$ yr^{-1}	None
g CH_4-C $animal^{-1}$ d^{-1}	None
% VS excreted	None
Derived or estimated	
NH_3	
g NH_3 LU^{-1}	Number of days over which measurements reported[1]
kg NH_3 LU^{-1}	Number of days over which measurements reported[1]
g NH_3-N t^{-1} LW d^{-1}	Mean animal weight during measurement or default mean weight
mg NH_3 kg^{-1} LW	Mean animal weight during measurement or default mean weight
g NH_3-N $animal^{-1}$	Number of days over which measurements reported[1]
g NH_3 $animal^{-1}$	Number of days over which measurements reported[1]
kg NH_3-N $animal^{-1}$	Number of days over which measurements reported[1]
kg NH_3 $animal^{-1}$	Number of days over which measurements reported[1]
g NH_3-N h^{-1}	Number of animals reported[2]
g NH_3-N d^{-1}	Number of animals reported[2]
g NH_3 d^{-1}	Number of animals reported[2]
g NH_3 min^{-1}	Number of animals reported[2]
μg NH_3 h^{-1}	Number of animals reported[2]
% TAN excreted	Proportion of TAN in excreta
g NH_3-N m^{-2} d^{-1}	Total floor area and number of animals in the building
g NH_3 m^{-2} d^{-1}	Total floor area and number of animals in the building
μg NH_3 m^{-2} s^{-1}	Total floor area and number of animals in the building
g NH_3-N m^{-2}	Total floor area, duration of measurement and number of animals in the building[1]
g NH_3 m^{-2}	Total floor area, duration of measurement and number of animals in the building[1]

(*continued*)

Table 1. Continued.

Units used in the papers examined	Data needed to convert units to g LU^{-1} d^{-1}, g $animal^{-1}$ d^{-1} or kg kg^{-1} N (for NH_3 and N_2O) and kg kg^{-1} VS (for CH_4)
N_2O	
mg N_2O kg LW^{-1} d^{-1}	Mean weight of animals within building
g N_2O kg^{-1} lwg	Mean liveweight gain over measurement period
g N_2O-N $animal^{-1}$	Number of days over which measurements reported[1]
g N_2O $animal^{-1}$	Number of days over which measurements reported[1]
g N_2O d^{-1}	Number of animals reported[2]
kg N_2O d^{-1}	Number of animals reported[2]
mg N_2O kg^{-1} LW	Mean weight of animals within building
g N_2O-N m^{-2} d^{-1}	Total floor area and number of animals in the building
mg N_2O-N m^{-2} d^{-1}	Total floor area and number of animals in the building
mg N_2O m^{-2} h^{-1}	Total floor area and number of animals in the building
mg N_2O m^{-2} d^{-1}	Total floor area and number of animals in the building
µg N_2O m^{-2} s^{-1}	Total floor area and number of animals in the building
CH_4	
mg CH_4 kg LW^{-1} d-1	Mean weight of animals within building
mg CH_4 kg^{-1} LW	Mean weight of animals within building
g CH_4 $animal^{-1}$	Number of days over which measurements reported[1]
g CH_4-C $animal^{-1}$	Number of days over which measurements reported[1]
g CH_4 d^{-1}	Number of animals reported[2]
kg CH_4 d^{-1}	Number of animals reported[2]
g CH_4 h^{-1}	Number of animals reported[2]
g CH_4 m^{-2} d^{-1}	Total floor area and number of animals in the building
mg CH_4 m^{-2} d^{-1}	Total floor area and number of animals in the building
mg CH_4 m^{-2} h^{-1}	Total floor area and number of animals in the building
mg CH_4 m^{-2} s^{-1}	Total floor area and number of animals in the building
Estimated	
NH_3	
g NH_3 hpu^{-1} d^{-1}	Relationship between hpu and LU reported by Rong *et al.*, 2014
g NH_3 hpu^{-1} h^{-1}	Relationship between hpu and LU reported by Rong *et al.*, 2014
N_2O	
g N_2O hpu^{-1} d^{-1}	Relationship between hpu and LU reported by Rong *et al.*, 2014
CH_4	
g CH_4 hpu^{-1} d^{-1}	Relationship between hpu and LU reported by Rong *et al.*, 2014
g CH_4 hpu^{-1} h^{-1}	Relationship between hpu and LU reported by Rong *et al.*, 2014
Not estimated	
NH_3	
mg NH_3-N g^{-1} urine-N	Requires data on N content of urine and urine output
g NH_3 kg^{-1} milk	Requires data on milk production per animal
% N milk	Requires data on milk production per animal and milk N content
g NH_3 kg HCW^{-1} d^{-1}	Requires data on HCW (hot carcase weight)
g NH_3 kg^{-1} DMI	Requires data on food dry matter intake
g NH_3 kg^{-1} N intake	Requires data on food intake and N content
% N intake	Requires data on food N intake
g NH_3 kg^{-1} manure	Requires data on manure deposited in building per animal
N_2O	
g N_2O kg^{-1} milk	Requires data on milk production per animal
g N_2O kg HCW^{-1} d^{-1}	Requires data on HCW
g N_2O kg^{-1} DMI	Requires data on food dry matter intake
mg N_2O kg^{-1} DMI	Requires data on food dry matter intake
mg N_2O g^{-1} N intake	Requires data on food intake and N content
g N_2O kg^{-1} N intake	Requires data on food intake and N content
mg N_2O kg $ingested^{-1}$ d^{-1}	Requires data on food intake and N content
CH_4	
g CH_4 kg^{-1} milk	Requires data on milk production per animal
g CH_4 kg^{-1} FPC milk	Requires data on milk production per animal and analysis
g CH_4 kg HCW^{-1} d^{-1}	Requires data on HCW
g CH_4 kg^{-1} DMI	Requires data on food dry matter intake
g CH_4 kg^{-1} NDF intake	Requires data on food dry matter intake and NDF content
g CH_4 kg^{-1} OM intake	Requires data on food dry matter intake and NDF content
mg CH_4 kg $ingested^{-1}$ d^{-1}	Requires data on food dry matter intake

Subscripts to Tables.
[1]Reported emission taken to be for whole measurement period.
[2]Reported emission taken to be for all the animals reported.

given but avoided more assumption than was necessary to provide a number that could be used in the calculation.

From emission per livestock unit to emission per animal. Where emissions per LU have been supplied, conversions to emissions per animal have been carried out by dividing the supplied emission by 500 then multiplying the product by the reported weight of the individual animals reported. For growing animals data were used as outlined above. It was not always possible to make the conversion from per LU to per animal from the data provided and in such cases the EF was estimated using default data and the result cited as estimated.

From emissions per unit time to emission per livestock unit and per animal. Where emissions were reported only per unit time then this emission was taken to be derived from the excreta of all the animals in the buildings during the entire measurement period and hence, where data were available, the emission was converted to emission per day, then per animal and then per LU as follows.

1. In some cases emissions were reported as a total weight of emission. As above, this emission was taken to be derived from the excreta of all the animals in the buildings during the entire measurement period. In such cases emission per day was derived by dividing the reported emission by the number of days during which measurements were made. This value was then divided by the number of animals reported to be in the building.
2. Conversion to emission per LU was carried out by dividing the emission per day by the number of animals and then multiplying by 500 divided by the reported animal weight. In the case of growing animals the adjustment was made using the approaches given in sections above; insofar as there were data available. Conversions could not always be made due to lack of data. In the absence of animal weights defaults could be used. However, in many cases the number of livestock within the building was not reported and hence it was not possible to attribute total emissions measured to emissions per animal or LU.
3. In some cases the number of days for a given measurement period was not provided, but the beginning and end dates of measurement were available. In these cases the number of days of measurement were taken to be the period between the start and end dates recorded and calculations otherwise carried out as indicated. In a few cases, mainly relating to broiler chickens, where no indication of the measurement period was provided, measurements were assumed to take place over the entire growing cycle. However, in many cases no data were reported indicating the length of the measurement period.

From emissions per m^2 of floor area to emission per livestock unit and per animal. Many emissions were reported per m^2 of floor area. Initially it was hoped that these could be converted to a total daily emission by multiplying by the total soiled floor area and adjusting the reported time units. However, there were just 368 data entries for the soiled floor area and most of those were from studies in which emissions were also reported in either one of the RqEF. Therefore, 120 observations reported per m^2 of floor area could not be converted into RqEFs.

Ba *et al.* [12] also converted reported data into a few emission units for their meta-analysis and the 'supplied' and 'derived' approaches outlined above are consistent with the approaches used by [12].

Estimated results

Where emissions could only be converted to the RqEFs by the use of external data, e.g. default values for annual N excretion for a class of livestock, e.g. mature dairy cows, these emissions have been 'estimated'. Where the paper did not cite livestock weights default values were used and the results cited as estimated. The sources used for these defaults are provided below.

Nitrogen and volatile solids excretion. There was a limited number of annual N excretion data for any livestock class in the database. Hence, where N emissions had not been reported as a proportion of N excreted by the animals, N emissions in those units had to be estimated.

The majority of data were from 11 countries: the USA, Canada, Sweden, Denmark, Germany, The Netherlands, Belgium, the UK, France, Italy and Austria. For data from these countries estimates were made as follows:

1. For the UK annual estimates of N excretion are available for all classes of livestock for use in the compilation of the UK Ammonia Emissions Inventory (UKAEI) [13]. Hence for UK results where N excretion was not reported, default values cited in the UKAEI were used.
2. Values for N and VS excretion are published in both the Austrian [14] and German National Inventory Reports (NIRs) [15].
3. For France a number of sources were used for data on livestock weights and annual N excretion and these are given in Table 2.
4. In addition to the UK, Austria and Germany, two of these countries (Denmark and The Netherlands, together with Switzerland) were represented at the EAGER group of ammonia

Table 2. Default values used for emissions from buildings. In some cases values have been rounded to nearest whole number.

Input	Country	Value	Source
Weight of dairy cow	The Netherlands	600 kg	[2]
Weight of dairy cow	Germany	600 kg	[2]
Weight of dairy cow	Austria	600 kg	[2]
Weight of dairy cow	Sweden	600 kg	[2]
Weight of dairy cow	Belgium	600 kg	[2]
Weight of dairy cow	US	600 kg	[2]
Weight of dairy cow	Canada	600 kg	[2]
Dairy cow annual N excretion	France	122 kg	[37]
Dairy cow annual N excretion	The Netherlands	134 kg	[16,17]
Dairy cow annual N excretion	UK	104 kg*	[13]
Dairy cow annual N excretion	Denmark	133 kg	[16,17]
Dairy cow annual N excretion	Austria	90 kg	[14]
Dairy cow annual N excretion	Germany	103 kg	[15]
Dairy cow annual N excretion	Sweden	117 kg	[22]
Dairy cow annual N excretion	Belgium	97 kg	[18]
Weight of beef animal	UK	340 kg	[13]
Weight of beef animal	Sweden	190 kg	[22]
Weight of beef animal	Austria	340 kg	[2]
Weight of beef animal	US	340 kg	[2]
Beef animal annual N excretion	UK	56 kg	[13]
Beef animal annual N excretion	Germany	46 kg	[15]
Beef animal annual N excretion	The Netherlands	45 kg	[16,17]
Beef animal annual N excretion	Denmark	45 kg	[16,17]
Beef animal annual N excretion	Sweden	36 kg	[22]
Beef animal annual N excretion	Austria	46 kg	[14]
Veal calf annual N excretion	UK	38 kg	[13]
Veal calf annual N excretion	Germany	45 kg	[15]
Veal calf annual N excretion	The Netherlands	36 kg	[16,17]
Veal calf annual N excretion	Denmark	27 kg	[16,17]
Finishing pig average weight	France	75 kg	[38]
Finishing pig average weight	The Netherlands	65 kg	[2]
Finishing pig average weight	Italy	65 kg	[2]
Finishing pig average weight	US	65 kg	[2]
Finishing pig average weight	Australia	65 kg	[2]
Finishing pig average weight	Spain	65 kg	[2]
Finishing pig annual N excretion	France	17.2 kg	[38,39]
Finishing pig annual N excretion	Germany	12.7 kg	[15]
Finishing pig annual N excretion	The Netherlands	13.7 kg	[16,17]
Finishing pig annual N excretion	Austria	9.0 kg	[14]
Finishing pig annual N excretion	Italy	13.8 kg	[21]
Finishing pig annual N excretion	UK	14.9 kg**	[13]
Finishing pig annual N excretion	Sweden	11.0 kg	[22]
Finishing pig annual N excretion	Spain	10.0 kg	[19]
Finishing pig annual N excretion	Belgium	11.1 kg	[18]
Finishing pig annual N excretion	Denmark	13.7 kg	[16,17]
Finishing pig annual N excretion	Hungary	12.5 kg	[20]
Weight of gestating sow	The Netherlands	225 kg	[2]
Weight of gestating sow	UK	225 kg	[2]
Weight of gestating sow	Germany	225 kg	[2]
Weight of gestating sow	Denmark	225 kg	[2]
Gestating sow annual N excretion	The Netherlands	38 kg	[16,17]
Gestating sow annual N excretion	Belgium	37.5 kg	[18]
Gestating sow annual N excretion	UK	22.3 kg	[13]
Gestating sow annual N excretion	Germany	36.6 kg	[15]
Gestating sow annual N excretion	Italy	36.6 kg	[21]
Gestating sow annual N excretion	Denmark	34.5 kg	[16,17]
Weight of farrowing sow	Canada	225 kg	[2]
Weight of weaned piglet	France	19.5 kg	[38]
Weight of weaned piglet	UK	13.5 kg	[13]
Weight of weaned piglet	Germany	20 kg	[2]
Weight of weaned piglet	The Netherlands	20 kg	[2]
Weight of weaned piglet	Denmark	20 kg	[2]
Weaned piglet annual N excretion	France	2.8 kg	[38,39]
Weaned piglet annual N excretion	Belgium	2.3 kg	[18]
Weaned piglet annual N excretion	Spain	1.9 kg	[19]
Weaned piglet annual N excretion	UK	4.2 kg	[13]
Weight of laying hen	UK	2.2 kg	[2]
Weight of laying hen	The Netherlands	2.2 kg	[2]
Weight of laying hen	US	2.2 kg	[2]
Weight of laying hen	France	1.8 kg	[40]
Weight of laying hen	Czech Republic	2.2 kg	[2]
Layer annual N excretion	UK	0.78 kg***	[13]
Layer annual N excretion	France	0.78 kg	[41]
Layer annual N excretion	Sweden	0.60 kg	[22]
Weight of broiler chicken	UK	1.0 kg	[2]
Broiler annual N excretion	UK	0.55 kg***	[13]
Weight of broiler chicken	US	1.0 kg	[2]

(*continued*)

Table 2. Continued.

Input	Country	Value	Source
Weight of broiler chicken	France	0.9 kg	[41]
Weight of broiler chicken	Sweden	1.0 kg	[2]
Broiler annual N excretion	Sweden	0.28 kg	[22]
Broiler annual N excretion	France	0.31 kg	[41]
Dairy cow daily VS excretion	Austria	4.6 kg°	[14]
Finishing pig daily VS excretion	Austria	0.29 kg	[14]
Default values for daily VS excretion for a range of livestock	All countries except Austria		[4]

*Annual values available for UK, this example is for 1998.
**Annual values available for UK, this example is for 2005.
***Annual values available for UK, these examples are for 2000.
°1998.

emission inventory modelers [16, 17] and default national data on N excretion for dairy cows, beef cattle and finishing pigs collated by EAGER for those countries were used in this study.

5. For Belgium [18, 19] and Hungary [20], information on national average N excretion for dairy cows, beef cattle, sows and finishing pigs from NIRs were used.
6. For Italy [21] and Sweden [22] data on N excretion were available from Codes of Good Agricultural Practice and Action Plans (AP) for manure use in Nitrate Vulnerable Zones (NVZ). For Italy the AP of Lombardy [21] was used since this AP is exhaustive and the Italian data analysed were derived from the region of Lombardy and those adjacent. The early date of this AP was appropriate since the data analysed was mainly from before 2006.

Default values used for emissions from buildings are given in Table 2

1. For the remaining countries estimates of N excretion were made using default data in chapter 10 of IPCC [4] and data on livestock weights reported in the appropriate papers reporting emissions.

The IPCC [4] methodology was also used to provide data on VS excretion.

Default national values used for N and CH_4 emissions from buildings are given in Table 2

Emissions reported per animal place. Emissions expressed per annual animal place (AAP) were taken to be equivalent to emissions expressed per animal. In consequence emissions reported per AAP were divided by 365 to give emissions per animal per day. For those classes of livestock subject to seasonal production cycles, e.g. broilers and finishing pigs, allowance has to be made for the time that the animal place is empty when calculating emissions per AAP.

Emissions reported per heat producing unit. Some studies only report emissions per heat producing unit (hpu). The data provided by Rong *et al.* [24] who reported emissions per hpu and per LU for dairy cows, were used to establish a relationship between emissions per hpu and per LU for dairy cows. To convert other emissions from dairy cows reported per hpu to LU, we multiplied by the mean factor of 1.0934 obtained from [24].

Validation of estimated data

Validation of default values of annual N excretion. Validation of the methodology and of some default values was carried out using studies in which NH_3-N emissions were supplied as both % N and per animal or LU per day. From these studies we could therefore estimate emissions of NH_3-N as % N using default data on N excretion and emissions supplied as per animal or LU per day and compare the result with those supplied as % N.

Three datasets supplied NH_3-N emissions as % N excreted [25,26; dairy cows] and [27; dairy cows and finishing pigs]. Of these three datasets two also reported emissions as g NH_3-N per animal per day [25, 27]. In the validation exercise emissions supplied as per animal per day were converted to emissions as g per kg N excreted using the appropriate default data on annual N excretion. Hence a comparison was made between NH_3-N emissions supplied as % N and those estimated as % N using default data.

For these two studies NH_3-N emissions expressed as % N were derived from NH_3-N emissions reported as g NH_3 per animal as follows:

NH_3-N, % N excreted = ((default N excretion animal^{-1} day^{-1})/100)/g NH_3-N animal^{-1} day^{-1}

Powell *et al.* [26] reported NH_3-N emissions as g NH_3-N per animal per day but provided data on N excretion per day. For this dataset comparison was made between emissions derived as % N, using reported data on N excretion, with emissions estimated as % N from emissions reported as per animal per day using default data on N excretion.

We were unable to validate our methods for estimating N_2O and CH_4 RqEFs due to insufficient studies for comparing with supplied RqEFs.

Validation of using a single estimate of annual N excretion for all relevant data. In some cases estimates of annual N excretion were available for each year since 1990, or at 5 yearly intervals from national Informative Inventory Reports (IIRs) or other documents, enabling a reasonable estimate of emissions of NH_3-N expressed as a proportion of N excreted when emissions were supplied or derived per animal. However, in some cases, e.g. UK data on N excretion by beef cattle and sheep, only one default value for N excretion was available over the entire time series. Using only one value for N excretion could lead to errors in the estimation of emissions per kg N excreted if livestock feeding or animal performance had changed significantly over the period. To assess the potential error of basing our estimates of NH_3-N emissions as a proportion of a single default value of N excreted we used UK data of annual values of N excretion per AAP for finishing pigs of mean weight 65 kg for the years 1990-2015 [13]. The measured emission was fixed at 5.0 g NH_3-N per animal per day to illustrate how variation in estimates of annual N excretion would influence the estimate of NH_3-N emission as a proportion of N excreted.

Validation of default values of mean livestock weights. The two datasets with the most data points for the relevant gases (19 and 16 respectively) which reported the weights of finishing pigs at the beginning and end of the measurement periods [29, 30] were used to compare examples of actual finishing pig weights with that used as a default from [2] (65 kg).

Emissions from manure stores

For emissions from manure stores the objective was to report emissions of NH_3, N_2O and CH_4 in the RqEF units of:

NH_3 as kg NH_3-N per kg of N put into store
NH_3 as kg NH_3-N per kg of TAN put into store
N_2O as kg N_2O-N per kg of N put into store
N_2O as kg N_2O-N per kg of TAN put into store
CH_4 as kg CH_4 per kg of VS put into store

As with emissions from livestock housing, supplied EFs were those in which the reported emission unit could be converted to a RqEF by a simple numeric adjustment. Table 3 lists all the different EFs used to express emissions of NH_3, N_2O and CH_4 from manure stores collated in the database. Table 3 also indicates whether the conversion of these EFs to the RqEFs was done on the basis of the RqEFs being supplied, derived or estimated.

Derived and estimated EFs

In order to express measured emissions as kg N per kg of N and TAN and as a kg CH_4 per kg of total VS put into the store the following information was needed:

1. Total amounts of NH_3, N_2O and CH_4 emitted.
2. Total amounts of N, TAN and VS put into the store.

Total amounts of NH_3, N_2O and CH_4 emitted. This information ought to have been available from all studies as the majority of studies reported emissions per unit of store surface area or total volume per unit of time. As long as the duration of the measurement had been reported, together with manure volume, total-N, TAN and VS contents of the manures calculating total emission as kg NH_3-N, N_2O-N and CH_4 was straightforward. Where this was the case, the resultant RqEFs were considered 'derived'. Where the necessary data on manure analysis was either absent or incomplete default values were used to provide the missing data, resulting in 'estimated' RqEFs. However, where the store surface area, or store volume were not reported it was not possible to estimate emissions in the RqEF units. Where reported emissions were expressed per t or m^3 of slurry or manure these emissions were taken to be the total emissions over the measurement period and hence expressed as kg N or CH_4 emitted per kg manure-N or manure-VS per t or m^3 of manure put into store. When emissions were expressed per t or m^3 of slurry or manure data on store surface area and manure quantities were not needed; emissions could be converted to the desired units using reported data on N, TAN and VS contents of the manure or default values.

Total amounts of N, TAN and VS put into the store. Where there were no data on manure analysis the same sources were used to obtain country-specific values of N and TAN per t of manure as those used to derive default values of N excretion (Section estimated results). For the amounts of N

Table 3. Units used to report emissions from manure stores. RAN = readily available N (considered equivalent to TAN.

Supplied	
NH_3	
% NH_3-N of initial N	None
% NH_3-N of initial TAN	None
% NH_3-N of initial RAN	None
N_2O	
% N_2O-N of initial N	None
% N_2O-N of initial TAN	None
% N_2O-N of initial RAN	None
CH_4	
% CH_4-C of initial VS	None
g CH_4-C kg^{-1} VS	None
Derived or estimated	
NH_3	
mg NH_3-N kg^{-1} N $week^{-1}$	Measurement duration
kg NH_3-N t^{-1}	N and TAN content per t manure
g NH_3-N t^{-1}	N and TAN content per t manure
g NH_3-N kg^{-1}	N and TAN content per t manure
g NH_3-N kg N^{-1} t^{-1}	N and TAN content per t manure
mg NH_3-N kg^{-1}	N and TAN content per t manure
g NH_3 t^{-1}	N and TAN content per t manure
kg NH_3-N m^{-3}	N and TAN content per m^3 manure
kg NH_3-N	Manure volume, N and TAN contents
g NH_3-N	Manure volume, N and TAN contents
g NH_3 m^{-3}	Manure weight, measurement duration, N and TAN content
mg NH_3 kg^{-1} d^{-1}	Manure weight, measurement duration, N and TAN content
g NH_3-N m^{-3} d^{-1}	Manure weight, measurement duration, N and TAN content
mg NH_3-N m^{-3} d^{-1}	Manure weight, measurement duration, N and TAN content
g NH_3-N m^{-2}	Store area, manure volume, N and TAN contents
g NH_3 m^{-2}	Store area, manure volume, N and TAN contents
kg NH_3-N yr^{-1}	Measurement duration, manure volume, N and TAN contents
kg NH_3 d^{-1}	Measurement duration, manure volume, N and TAN contents
g NH_3 min^{-1}	Measurement duration, manure volume, N and TAN contents
g NH_3-N m^{-2} d^{-1}	Store area, measurement duration, manure volume, N and TAN contents
mg NH_3-N m^{-2} h^{-1}	Store area, measurement duration, manure volume, N and TAN contents
µg NH_3-N m^{-2} s^{-1}	Store area, measurement duration, manure volume, N and TAN contents
g NH_3 m^{-2} h^{-1}	Store area, measurement duration, manure volume, N and TAN contents
mg NH_3 m^{-2} h^{-1}	Store area, measurement duration, manure volume, N and TAN contents
mg NH_3 m^{-2} min^{-1}	Store area, measurement duration, manure volume, N and TAN contents
µg NH_3 m^{-2} s^{-1}	Store area, measurement duration, manure volume, N and TAN contents
ng NH_3 cm^{-2} s^{-1}	Store area, measurement duration, manure volume, N and TAN contents
kg NH_3-N ha^{-1} d^{-1}	Store area, measurement duration, manure volume, N and TAN contents
kg NH_3 ha-1 d^{-1}	Store area, measurement duration, manure volume, N and TAN contents
kg NH_3-N ha^{-1} yr^{-1}	Store area, measurement duration, manure volume, N and TAN contents
N_2O	
kg N_2O-N t^{-1}	N and TAN content per t manure
g N_2O-N t^{-1}	N and TAN content per t manure
g N_2O-N kg N^{-1} t^{-1}	N and TAN content per t manure
mg N_2O-N kg^{-1}	N and TAN content per t manure
g N_2O t^{-1}	N and TAN content per t manure
g N_2O kg^{-1}	N and TAN content per t manure
mg N_2O kg^{-1}	N and TAN content per t manure
kg N_2O-N m^{-3}	N and TAN content per t manure
kg N_2O-N	Manure volume, N and TAN contents
g N_2O t^{-1} yr^{-1}	Measurement duration, N and TAN content of manure
mg N_2O kg^{-1} d^{-1}	Measurement duration, N and TAN content of manure
g N_2O m^{-3}	Measurement duration, N and TAN content of manure
g N_2O-N m^{-3} d^{-1}	Measurement duration, N and TAN content of manure
mg N_2O-N m^{-3} d^{-1}	Measurement duration, N and TAN content of manure
g N_2O-N m^{-2}	Store area, manure volume, manure N and TAN content
g N_2O m^{-2}	Store area, manure volume, N and TAN contents
kg N_2O d^{-1}	Duration of measurements, manure volume and manure N and TAN
g N_2O-N m^{-2}	Store area, manure volume, manure N and TAN content
g N_2O m^{-2}	Store area, manure volume, N and TAN contents
g N_2O-N m^{-2} d^{-1}	Store surface area, , duration of measurements, manure volume and manure N and TAN
g N_2O m^{-2} d^{-1}	Store surface area, , duration of measurements, manure volume and manure N and TAN
mg N_2O m^{-2} h^{-1}	Store surface area, , duration of measurements, manure volume and manure N and TAN
µg N_2O-N m^{-2} s^{-1}	Store surface area, , duration of measurements, manure volume and manure N and TAN
µg N_2O m^{-2} s^{-1}	Store surface area, , duration of measurements, manure volume and manure N and TAN
ng N_2O m^{-2} s^{-1}	Store surface area, duration of measurements, manure volume and manure N and TAN
kg N_2O ha^{-1} d^{-1}	Store area, measurement duration, manure volume, N and TAN contents
CH_4	
g CH_4-C t^{-1}	VS content of manure
% CH_4-C of initial C	VS content of manure C
l CH_4 kg^{-1} VS	Density of CH_4
g CH_4 t^{-1}	VS content of manure
g CH_4 kg^{-1}	VS content of manure
mg CH_4 kg^{-1}	VS content of manure
kg CH_4-C t^{-1}	VS content of manure
g CH_4-C kg^{-1}	VS content of manure

(*continued*)

kg CH_4 m^{-3}	VS content of manure
g CH_4 m^{-3}	VS content of manure
mg CH_4 l^{-1}	VS content of manure
kg CH_4-C m^{-3}	VS content of manure
CH_4-C t^{-1} DM	DM and VS content of manure
mg CH_4-C kg^{-1} d^{-1}	Measurement duration and VS content
l CH_4 l^{-1}	Density of CH4 and VS content of manure
g CH_4 m-3 d^{-1}	Measurement duration, manure volume and VS content
kg CH_4 m^{-2}	Store area, manure volume and VS content
g CH_4-C m^{-2}	Store area, manure volume and VS content
kg CH_4 d^{-1}	Measurement duration, manure volume and VS content of manure
g CH_4 h^{-1}	Measurement duration, manure volume and VS content of manure
g CH_4 min^{-1}	Measurement duration, manure volume and VS content of manure
mg CH_4 m^{-3} h^{-1}	Measurement duration, manure volume and VS content
g CH_4-C m^{-3} d^{-1}	Measurement duration, manure volume and VS content
mg CH_4 kg-1 d^{-1}	Measurement duration and VS content of manure
g CH_4 m^{-2} d^{-1}	Store surface area, duration of measurements, manure volume and VS content
g CH_4 m^{-2} h^{-1}	Store surface area, duration of measurements, manure volume and VS content
mg CH_4 m^{-2} h^{-1}	Store surface area, duration of measurements, manure volume and VS content
µg CH_4 m^{-2} s^{-1}	Store surface area, duration of measurements, manure volume and VS content
ng CH_4 cm^{-2} s^{-1}	Store surface area, duration of measurements, manure volume and VS content
kg CH_4 m^{-2} yr^{-1}	Store surface area, duration of measurements, manure volume and VS content
kg CH_4 ha^{-1} d^{-1}	Store surface area, duration of measurements, manure volume and VS content
g CH_4-C m^{-2} d^{-1}	Store surface area, duration of measurements, manure volume and VS content
kg CH_4-C ha^{-1} d^{-1}	Store surface area, duration of measurements, manure volume and VS content
kg CH_4-C	Measurement duration, manure volume and VS content of manure
l CH_4 m^{-3} d^{-1}	Measurement duration, density of CH4 and VS content of manure
l CH_4 l^{-1} d^{-1}	Measurement duration, density of CH4 and VS content of manure
m^3 CH_4 m^{-2}	Store area, manure volume, density of CH4 and VS content of manure
Not estimated	
NH_3	
g NH_3-N LU^{-1} h^{-1}	Need numbers of animals which are not available and no suitable default
kg NH_3-N $animal^{-1}$ yr^{-1}	Need numbers of animals which are not available and no suitable default
kg NH_3-N kg LW^{-1} yr^{-1}	Need numbers of animals which are not available and no suitable default
kg NH_3 $animal^{-1}$ d^{-1}	Need numbers of animals which are not available and no suitable default
kg NH_3 $animal^{-1}$ yr^{-1}	Need numbers of animals which are not available and no suitable default
N_2O	
g N_2O $animal^{-1}$	Need numbers of animals which are not available and no suitable default
g N_2O $animal^{-1}$ d^{-1}	Need numbers of animals which are not available and no suitable default
g N_2O-N $animal^{-1}$ $week^{-1}$	Need numbers of animals which are not available and no suitable default
g N_2O $animal^{-1}$ yr^{-1}	Need numbers of animals which are not available and no suitable default
g N_2O kg^{-1} lwg	Need numbers of animals which are not available and no suitable default
CH_4	
kg CH_4 $animal^{-1}$ d^{-1}	Need numbers of animals which are not available and no suitable default
g CH_4 $animal^{-1}$ d^{-1}	Need numbers of animals which are not available and no suitable default
g CH_4 $animal^{-1}$ $week^{-1}$	Need numbers of animals which are not available and no suitable default
g CH_4 $animal^{-1}$ yr^{-1}	Need numbers of animals which are not available and no suitable default
kg CH_4 $animal^{-1}$ yr^{-1}	Need numbers of animals which are not available and no suitable default
g CH_4 kg^{-1} lwg	Need numbers of animals which are not available and no suitable default
% MCF	Need numbers of animals, feed intake and components which are not available

and proportions of TAN in stored manures some additional sources were used. These were for the UK [23]; Germany and Sweden [30] and for France sources cited in [31]. For data from other countries 'standard' values for the amounts of N in the different manures were taken from those cited in [32]. These report average values for EU-15 countries so applicability to results obtained outside Europe may be questioned. However, dry matter contents recorded in the database from studies outside of Europe were comparable to those reported in [32], so we concluded those values were reasonable to use.

Default values used for emissions from stores are given in Table 4.

Validation of estimated EFs

Validation of estimated RqEFs for stored manures was carried out by comparing reported emissions expressed as % TAN with emissions estimated using default values for the proportion of TAN and the appropriate emission reported as % N. We considered this was the most challenging comparison as estimated values expressed as % TAN depended upon very broadly-based estimates of the default values for the proportions of manure-N present as TAN (see section estimated results). For this exercise, we used data reported by [33] (raw and co-digested pig slurries) and [34] (dairy-cattle and chicken-manure slurries), who reported NH_3-N emissions as % TAN. For the validation we used default TAN values with emissions reported by those workers as %N.

Validation of default N values of manure analysis. One dataset [35] reported the total N contents of 12 slurry samples that could be compared with a default used from the same country [14]. The mean of the values reported was compared with the relevant default value.

Table 4. Default values used for emissions from stores.

Input	Country	Value	Source
N content of cattle slurry, kg m^{-3}	Austria	3.4	[14]
N content of cattle slurry, kg m^{-3}	Germany	5.0	[30]
N content of pig slurry, kg m^{-3}	Austria	6.4	[14]
N content of finishing pig slurry, kg m^{-3}	France	6.0	[31]
N content of pig slurry, kg m^{-3}	Germany	6.0	[30]
N content of broiler manure, kg m^{-3}	UK	30	[23]
Proportion of TAN in dairy slurry	Japan	0.58	[32]
Proportion of TAN in dairy slurry	New Zealand	0.58	[32]
Proportion of TAN in dairy slurry	US	0.58	[32]
Proportion of TAN in cattle slurry	UK	0.50	[23]
Proportion of TAN in cattle slurry	Austria	0.50	[14]
Proportion of TAN in cattle slurry	Switzerland	0.58	[32]
Proportion of TAN in pig slurry	UK	0.60	[23]
Proportion of TAN in pig slurry	Austria	0.65	[14]
Proportion of TAN in pig slurry	US	0.71	[32]
Proportion of TAN in finishing pig slurry	France	0.64	[31]
Proportion of TAN in gestating sow slurry	France	0.77	[31]
Proportion of TAN in weaned piglet slurry	France	0.52	[31]
Proportion of TAN in layer slurry	US	0.47	[32]
Proportion of TAN in solid cattle manure	Sweden	0.47	[30]
Proportion of TAN in solid cattle manure	Switzerland	0.27	[32]
Proportion of TAN in solid cattle manure	Germany	0.28	[30]
Proportion of TAN in cattle and pig FYM	UK	0.25	[23]
Proportion of TAN in solid pig manure	Germany	0.28	[30]
Proportion of TAN in pig FYM (straw-based)	France	0.32	[31]
Proportion of TAN in solid pig manure	Sweden	0.39	[30]
Proportion of TAN in poultry manure	US	0.32	[32]
Proportion of TAN in solid layer manure	Sweden	0.48	[30]
Proportion of TAN in broiler manure	UK	0.4	[23]
Proportion of TAN in dairy manure compost	Japan	0.27	[32]
Proportion of TAN in beef manure compost	China	0.27	[32]
Proportion of TAN in pig manure compost	China	0.32	[32]
Proportion of TAN in pig manure compost	Vietnam	0.32	[32]
Proportion of TAN in pig manure compost	Japan	0.32	[32]
Proportion of TAN in poultry manure compost	Japan	0.28	[32]

Table 5. Number of emissions from buildings housing livestock supplied, derived or estimated within the data set.

	g N LU^{-1} d^{-1}	g N $animal^{-1}$ d^{-1}	kg NH_3-N, N_2O-N kg N^{-1} excreted or kg CH_4 VS^{-1} excreted
NH_3			
Supplied	444	690	72
Derived	432	345	49
Estimated	334	174	1077
Total	1210	1209	1198
N_2O			
Supplied	82	188	16
Derived	149	48	23
Estimated	79	76	273
Total	310	312	312
CH_4			
Supplied	139	220	0
Derived	149	72	0
Estimated	59	60	351
Total	347	352	337

Results and discussion

Housing

Table 5 reports the number of emissions reported in the RqEF units (g N LU^{-1} d^{-1}, g N $animal^{-1}$ d^{-1}, kg N kg N^{-1} excreted) and the number of RqEFs either derived or estimated, where the latter used default values for mean animal weight, annual N excretion etc. By deriving and estimating emissions using the methods described we were able to increase the number of emissions expressed in the RqEFs from, for example, 444 to 1210 for NH_3-N emissions as kg N LU^{-1} d^{-1}, and from 16 to 312 for N_2O-N emissions expressed as kg N kg N^{-1} excreted.

We have identified several limitations to the derivation of RqEFs. Firstly, of the 2003 emission unit observations of NH_3, N_2O and CH_4 emissions, only *c.* 1400 have reported the weight of the animals in some way. Reporting was as either per average live weight (519 observations, appropriate for mature animals such dairy cows and laying hens) or the live weight at the start (882 observations) or end (837 observations) of the measurements period, appropriate for growing animals such as finishing pigs and broilers (Table 6).

Secondly, only 186 records of N excretion per animal were reported. These limitations were overcome by using default data (section estimated results). However, where emissions were reported per unit soiled floor area the lack of data on this factor (368 records in total) was a greater limitation as there is no acceptable default value. We conjectured that there might be buildings which had been used for more than one study and that if the soiled floor area was reported in one study then it could be applied to another study where the same building was used but the floor area had not been cited. However, we did not find any instances where this occurred.

We considered if the surface area could be obtained from another study by the same authors, assuming the same facility was used in both studies. However, we concluded this was too uncertain and, in many cases, there were no other studies reported by the same author(s).

Table 6. **Records related to emissions of NH_3, N_2O and CH_4 from buildings housing livestock.**

Factor	Number of values reported
Emissions	2003
Duration of measurements	1128
Number of animals	1765
Number of livestock units present	0
Weight at start of measurement	882
Weight at end of measurement	837
N excretion per animal	186
TAN excretion per animal	0
Average live weight	519
Live weight gain per day	605
Fouled floor area	368
Food dry matter intake	124
Food N intake	0
Milk yield per animal	280

Storage

Table 7 provides the number of emissions in the RqEFs for each of the three gases of interest (NH_3, N_2O and CH_4) according to whether those emissions were supplied, derived or estimated.

The major limitation in the data is that a large proportion of the data reported on an area basis could not be converted to a total emission over the measurement period because no data were provided on either store surface area, store volume, manure total-N, TAN or VS content. Where emissions were reported per unit weight or volume of manure there was a greater likelihood of making a conversion. However, in these cases recourse had to be made to default values for the N and TAN contents of manures (section estimated results). More information on data availability is given in Table 8.

There were only 859 records of the initial N content of the manure, and 656 of the initial TAN content of the manure (Table 8).

Validation of estimated EFs

Emissions from buildings housing livestock

Validation of default values of annual N excretion. The regression derived from the three datasets in which emissions, represented as kg N per kg N excreted, were estimated using the approach reported in section 2.1.4. (27 values, Figure 1) suggests a very good correlation ($R^2 = 0.97$) between estimated and supplied emissions.

Validation of using a single estimate of annual N excretion for all relevant data. The data on N excretion per AAP by finishing pigs for 1990 to 2015 [13] decreased by 24% over 25 years. Hence over 25 years an NH_3-N emission of 5 kg animal^{-1} day^{-1} is equivalent to between 0.10 (1990) and 0.14 (2015) kg kg^{-1} N excreted, i.e. a maximum error of 40%. This reduction in the emission expressed as a proportion of N excreted reflects the 40% decrease in annual N excretion arising from gradual reduction in the protein concentration in diets fed to finishing pigs. This estimate for finishing pigs is at the upper range of likely errors.

Table 8. **Records related to emissions of NH_3, N_2O and CH_4 from manure stores.**

Factor	Number of values reported
Emissions	1551
Duration of measurements	1217
Store surface area	788
Store volume	911
Volume of manure in store	591
N content of manure	859
TAN content of manure	656
VS content of manure	22
Livestock numbers	6
Livestock weight	0
Dry matter intake	6
Milk yield per animal	0

Table 7. **Number of emission factors from manure stores supplied, derived or estimated within the data set.**

	NH_3-N		N_2O-N		CH_4
	kg N kg^{-1} N stored	kg N kg^{-1} TAN stored	kg N kg^{-1} N stored	kg N kg^{-1} TAN stored	kg CH_4 kg^{-1} VS stored
Supplied	154	13	126	13	90
Derived	183	158	89	87	14
Estimated	80	252	37	150	8
Total	417	423	353	250	112

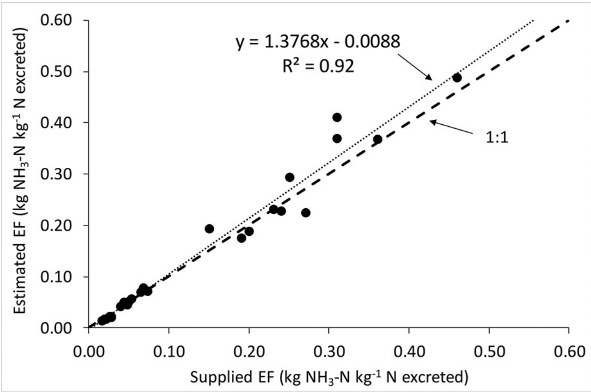


Figure 1. Correlation between supplied and estimated emissions of ammonia expressed as proportion of N excreted.
Supplied EFs were those in which the reported emission unit could be converted to a RqEF by a simple numeric adjustment. Estimated emissions can only be converted to the RqEFs by the use of external data, e.g. default values for annual N excretion.

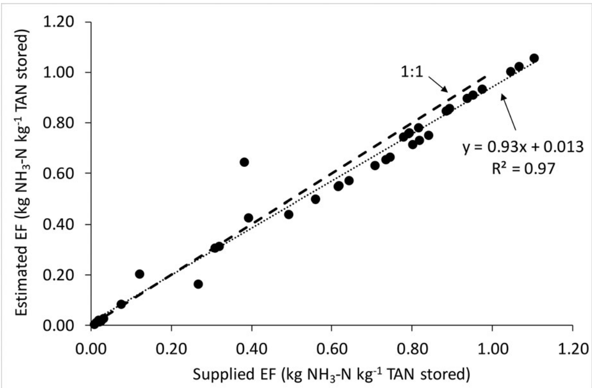


Figure 2. **Correlation between supplied and estimated emissions of ammonia expressed as proportion of TAN put into the store.**

Over the same period annual N excretion by dairy cows increased by 31% [13]

Validation of default values of mean livestock weights. The average finishing pig weight reported by [28] was 64.7 kg and the average weight reported by [29] was 68.4 kg. Both results are close to the default value of 65 kg [2].

Emissions from manure stores

Validation of estimating emissions as kg N per kg TAN stored. The supplied and estimated values for NH_3-N emissions expressed as kg kg^{-1} TAN, were in very good agreement (Figure 2):

EF_{est} = estimated EF (kg NH_3-N kg^{-1} TAN stored)
a = 0.93
EF_{sub} = supplied EF (kg NH_3-N kg^{-1} TAN stored)
b = 0.013
$R^2 = 0.97$
$P < 0.001$.

Validation of default N values of manure analysis. The mean N content of the 12 samples of cattle slurry reported by [35] was 3.7 kg N m^{-3}. This was *c.* 10% greater than the default value of 3.4 kg Nm^{-3} [14].

This validation exercise demonstrates that housing EFs based on total N can be estimated with a reasonable degree of confidence. While the effect of diet suggests RqEFs may have an associated error of up to 40%, such a large error would only apply when the national default values provided only one value for the entire time series. In practice for pigs and dairy cattle N excretion values were often provided for each year of the time series or for groups of 5 years. Furthermore, the storage validation using EFs as % of TAN was very good, and could arguably be just as relevant for EFs based on % total N.

We were unable to perform a similar validation for N_2O and CH_4 RqEFs due to insufficient data for comparative purposes. However, in the case of N_2O, since both N_2O-N and NH_3-N RqEFs are derived from manure total N (for housing and storage RqEFs) or from manure TAN content (for storage RqEFs), we are reasonably confident that our method is equally robust for N_2O-N RqEFs.

Our main concern lies with estimated RqEFs for CH_4 based on VS, given we were unable to validate our method. The primary source of VS data used for estimating CH_4 RqEFs was the latest IPCC guidelines, which were developed using information from a review of the literature on dietary effects, with input from regional experts [4]. Faecal VS content and total N of dairy cattle excreta are strongly influenced by dietary dry matter (DM) intake, acid detergent fibre (ADF) content and crude protein (CP) content [36]. These workers found that the error in predicting VS and N excreted using DM intake, ADF and CP was similar, which suggests that, in the absence of validation of our proposed method, the estimated dairy cattle RqEFs for CH_4 may have an error similar to that for NH_3 and N_2O. Thus, assuming a similar effect of diet on beef cattle, swine and poultry, estimated values may still be useful for determining drivers of emissions and assessing RqEFs, as long as these data are treated with caution. When combined with more robustly determined EFs, we advise researchers to label these estimated values as lower quality data. While the same recommendation applies to estimated NH_3 and N_2O EFs, this tiered approach to the quality of data is more pertinent to CH_4 RqEFs until sufficient data is available for validation purposes.

Table 9. Recommended information to be included in publications to aid conversion of emission units.

Building	Comments
Mean animal weight during measurement period or weight at the beginning and end of the measurement period	
Mean number of animals in the building during the measurement period	
Mean N excretion, expressed per day or per year, during the measurement period or mean VS excretion for CH_4 measurements	
Duration of the measurement period.	
Total floor area from which emissions, when emissions are expressed per unit of floor area	
Manure stores	
Duration of measurements	
Store surface area	
Store volume	
Volume of manure in store	The volume of manure in store needs to be provided as this will usually be less than the total store volume
Total N content of manure, per unit weight	Reporting needs to indicate if this is on a dry or fresh weight basis
TAN content of manure, per unit weight	Reporting needs to indicate if this is on a dry or fresh weight basis
VS content of manure, per unit weight	Reporting needs to indicate if this is on a dry or fresh weight basis
Dry matter content of manure	To enable conversion of dry weight manure N, TAN or VS analyses to fresh weight
Livestock numbers (when emissions are reported per animal of LU)	To enable estimation of manure voided by the livestock.
Length of housing period over which manure was collected for storage	To enable estimation of manure voided by the livestock.
Livestock weight (when emissions are reported per animal of LU)	To enable estimation of manure voided by the livestock.
Proportion of the day livestock were housed during the period over which manure was collected for storage	To enable estimation of manure voided by the livestock.

Recommended key factors for reporting

In general, papers that reported emissions per LU or per animal tended to provide data on mean animal weights. However, data on N excretion was less often reported. The omission that most frequently precluded conversion of emissions to the reported unit was the total floor area of buildings from which emissions were reported per unit area of floor. Based on our experience with conversion of reported NH_3, N_2O and CH_4 emissions to RqEFs, we have provided a list of recommended key factors to include in papers presenting measured emissions of CH_4, N_2O and NH_3 from livestock buildings and manure stores (Table 9).

Conclusions

The methodology developed greatly increased the number of RqEFs available for use in inventory compilation. Validation of the method using data reporting NH_3-N emissions from livestock buildings and from slurry stores indicated very good correlation between emissions estimated using the methodology and reported emissions ($R^2 = 0.97$ and 0.97, respectively). A similar comparison of estimated and supplied EFs was not possible for N_2O and CH_4 emissions from housing or storage due to insufficient suitable data. We have developed a list of recommended information for inclusion in publications reporting emissions that will enable other workers to utilize this methodology. The methodology will enable researchers to convert a wide range of emission units into RqEFs and open up opportunities for increased use of published data. In particular the adoption of this methodology may enable national emission inventories to be calculated with greater accuracy and to enable the development of Tier 3 inventory methodologies. The expression of more data in RqEFs may also contribute to better quantification of management systems and techniques to reduce emissions of N_2O, NH_3 and CH_4.

Note

1. https://www.mels-project.eu/

Acknowledgements

This work was supported by the New Zealand Government under MPI contract number A26460 to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases.

Disclosure statement

There are no conflicts of interest arising from this work for any of the authors.

Funding

This work was supported by the New Zealand Government under MPI contract number A26460 to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases.

ORCID

T. J. van der Weerden http://orcid.org/0000-0002-6999-2584
M. Hassouna http://orcid.org/0000-0001-8994-9690
B. Amon http://orcid.org/0000-0001-5650-1806

Data availability statement

Not applicable.

References

1. O'Mara FP. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. Anim Feed Sci Tech. 2011;166-167:7–15. doi:10.1016/j.anifeedsci.2011.04.074.
2. EMEP/EEA. EMEP/EEA air pollutant emission inventory guidebook. Chapter 3 Agriculture. 2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019.
3. GRA. Manure Management Network. 2020. https://globalresearchalliance.org/research/livestock/networks/manure-management-network/. Accessed 15 October 2020.
4. IPCC. Chapter 10: Emissions from livestock and manure management. In: 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories; 2019. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html. Accessed on 28th October 2021.
5. Cowell D, ApSimon HM. Cost-effective strategies for the abatement of ammonia emissions from european agriculture. Atmos Environ. 1998;32(3):573–580. doi:10.1016/S1352-2310(97)00203-3.
6. Webb J, Misselbrook TH. A mass-flow model of ammonia emissions from UK livestock production. Atmos Environ. 2004;38(14):2163–2176. doi:10.1016/j.atmosenv.2004.01.023.
7. Dämmgen U, Webb J. The development of the EMEP/CORINAIR guidebook with respect to the emissions of different nitrogen and carbon species from animal production. Agr Ecosyst Environ. 2006;112(2-3):241–248. doi:10.1016/j.agee.2005.08.025.
8. GRA. Dataman. 2020. https://globalresearchalliance.org/research/livestock/collaborative-activities/dataman/. Accessed 15 October 2020.
9. Beltran I, van der Weerden TJ, Alfaro MA, et al. DATAMAN: a global database of nitrous oxide and ammonia emission factors for excreta deposited by livestock and land-applied manure. J Environ Qual. 2021;50(2):513–527. doi:10.1002/jeq2.20186.
10. Vigan A, Hassouna M, Guingand N, et al. Development of a database to collect emission values for livestock systems. J Environ Qual. 2019;48(6):1899–1906. doi:10.2134/jeq2019.01.0007.
11. Hassouna M, van der Weerden TJ, Beltran I, et al. DATAMAN: a global database of methane, nitrous oxide and ammonia emission factors for livestock housing and outdoor storage of manure. in prep.
12. Ba S, Qu Q, Zhang K, et al. Meta-analysis of greenhouse gas and ammonia emissions from dairy manure composting. Biosyst Eng. 2020;193:126–137. doi:10.1016/j.biosystemseng.2020.02.015.
13. Misselbrook TH, Gilhespy SL, Cardenas LM, et al. Inventory of ammonia emissions from UK agriculture 2015. London: Defra Contract SCF0102, Inventory Submission Report; 2016.
14. Anderl A, Friedrich A, Gangl M, et al. Austria's national inventory report 2020. Vienna (AT): Umweltbundesamt GmbH Spittelauer Lände 5, 1090; 2020.
15. Anon. Germany: 2019 National Inventory Report (NIR); 2019. https://unfccc.int/documents/194930.
16. Reidy B, Dämmgen U, Döhler H, et al. Comparison of models used for national agricultural ammonia emission inventories in Europe: liquid manure systems. Atmos Environ. 2008;42(14):3452–3464. doi:10.1016/j.atmosenv.2007.04.009.
17. Reidy B, Webb J, Misselbrook TH, et al. Comparison of models used for national agricultural ammonia emission inventories in Europe: litter-based manure systems. Atmos Environ. 2009;43(9):1632–1640. doi:10.1016/j.atmosenv.2008.12.015.
18. Anon. Informative inventory report about Belgium's air emissions submitted under the Convention on Long Range Transboundary Air Pollution CLRTAP and National Emission Ceiling Directive NECD. Belgium: Flemish Environment Agency (VMM), Walloon Agency for Air and Climate (AWAC), Walloon Public Service; 2018.
19. Anon. Spain, informative inventory report 1990-2016. Directorate-General for environmental quality and assessment and natural environment, secretariat of state for environment. Spain: Spanish Ministry of Agriculture and Fishing, Food and Environment, (ES); 2018.
20. Kis-Kovács G, Tarczay K, Kőbányai K, et al. Informative inventory report Hungary 2016. Hungary: Compiled by the Hungarian Meteorological Service, Unit of National Emissions Inventories; 2018.
21. Anon. Regional council resolution no. 8/3439 of 7 November 2006. Adaptation of the lombardy region action programme as of regional council resolution no. 17149/96 for the protection and remediation of waters polluted by nitrates of an agricultural origin for farms located in vulnerable zones, pursuant to legislative decree no. 152 of 3 April 2006, article 92 and ministerial decree no. 209 of 7 April 2006. Italy: Lombardy Region Official Gazette; 2006.
22. Anon. Rules amending the Swedish Board of Agriculture rules (SJVFS 2004:62) on environmental concerns in agriculture as regards plant nutrients and the Swedish Board of Agriculture general guidance (2005:1) on the storage and application of fertilisers, etc. Sweden: Swedish Board of Agriculture statutes, Statens jordbruksverk, 551 82 Jönköping, (SE); 2009.
23. Anon. Fertilizer manual (RB209). 8th ed. Norwich: TSO, (UK); 2010. www.tso.co.uk.
24. Rong L, Liu D, Pedersen EF, et al. Effect of climate parameters on air exchange rate and ammonia and methane emissions from a hybrid ventilated dairy cow building. Energy Build. 2014;82:632–643. doi:10.1016/j.enbuild.2014.07.089.
25. Aguerre MJ, Wattiaux MA, Hunt T, et al. Effect of dietary crude protein on ammonia-N emission measured by herd nitrogen mass balance in a freestall dairy barn managed under farm-like conditions. Animal. 2010;4(8):1390–1400. doi:10.1017/S1751731110000248.

26. Powell JM, Broderick GA, Misselbrook TH. Seasonal diet affects ammonia emissions from Tie-Stall dairy barns. J Dairy Sci. 2008;91(2):857–869. doi:10.3168/jds.2007-0588.
27. Gilhespy SL, Webb J, Chadwick DR, et al. Will additional straw bedding in building housing cattle and pigs reduce ammonia emissions? Biosyst Eng. 2009; 102(2):180–189. doi:10.1016/j.biosystemseng.2008.10.005.
28. Granier R, Guingand N, Massabie P. Influence du niveau d'hygrométrie, de la température et du taux de renouvellement de l'air sur l'évolution des teneurs en ammoniac. [Influence of moisture, temperature and ventilation rate on indoor ammonia concentrations]. J Rech Porcine. 1996;28:209–216.
29. Guingand N, Rugani A. Lisier flottant: une technique simple pour réduire les émissions d'ammoniac et d'odeurs en porcherie. [Slurry removal: a simple way to reduce ammoniac and odours in piggeries]. J Rech Porcine. 2016;48:171–176.
30. Webb J, Sørensen P, Velthof G, et al. Study on variation of manure N efficiency throughout Europe. UK, Ricardo plc, Harwell International Business Centre, Didcot; 2011. https://ec.europa.eu/environment/water/water-nitrates/pdf/Man_N_Eff_Final%20Report.pdf
31. Levasseur P. Composition des effluents porcins et de leurs co-produits de traitement – Quantités produites. [Swine manure and process by-products composition and quantities]. Paris, France: Edition ITP; 2005.
32. Menzi H. Manure management in Europe: results of a recent survey. In: Proceedings of the 10th Conference of the FAO/ESCORENA Network on Recycling Agricultural, Municipal and Industrial Residues in Agriculture (RAMIRAN); May14-18 2002; Strbske Pleso, Slovak Republic. p 93–102.
33. Regueiro I, Coutinho J, Gioelli F, et al. Acidification of raw and co-digested pig slurries with alum before mechanical separation reduces gaseous emission during storage of solid and liquid fractions. Agr, Ecosys Environ. 2016;227:42–51. doi:10.1016/j.agee.2016.04.016.
34. Termeer WC, Warman PR. Use of mineral amendments to reduce ammonia losses from dairy-cattle and chicken-manure slurries. Bioresource Technol. 1993;440:217–222.
35. Amon B, Kryvoruchko V, Amon T, et al. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agr Ecosyst Environ. 2006; 112:53–162.
36. van Lingen HJ, Fadel JG, Bannink A, et al. Multi-criteria evaluation of dairy cattle feed resources and animal characteristics for nutritive and environmental impacts. Animal. 2018;12(s2):S310–S320. doi:10.1017/S1751731118001313.
37. Peyraud JL, Cellier P, Donnars C, et al. Les flux d'azote en élevage de ruminants. [Nitrogen flows in cattle farms]. 19. Paris, France: Rencontres Recherches Ruminants (3R), Paris (FR), Institut de l'Elevage – INRA; 2012.
38. Dourmad JY, Levasseur P, Daumer M, et al. Évaluation des rejets d'azote, phosphore, potassium, cuivre et zinc des porcs. [Assessment of releases of nitrogen, phosphorus, potassium, copper and zinc from pigs.]. Paris, France: RMT Elevages et Environnement; 2015.
39. IFIP. Résultats des élevages GTTT GTE [Results concerning the technical management of sow herds (GTTT) and the technico-economic management (GTE) 2016]. 2016. https://ifip.asso.fr/fr/resultats-economiques-gttt-graphique.html. see online 09/10/2020.
40. CORPEN. Estimation des rejets d'azote - phosphore - potassium calcium - cuivre - et zinc par les élevages avicoles, Mise à jour des références CORPEN-Volailles de 2006 [Poultry nitrogen, phosphorus, potassium calcium and zinc excretion - Update of 2006 references]. p. 63. https://agriculture.gouv.fr/sites/minagri/files/documents/pdf/sandrinel_Brochure_CORPEN_Volailles_revisee_21_JUIN_2013_DEFINITIVE_cle01d483.pdf. See online 09/10/2020