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DATASET ARTICLE

DATAMAN: A global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure

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Abstract

Livestock manure management systems can be significant sources of nitrous oxide (N_2O), methane (CH_4), and ammonia (NH_3) emissions. Many studies have been conducted to improve our understanding of the emission processes and to identify influential variables in order to develop mitigation techniques adapted to each manure management step (animal housing, outdoor storage, and manure spreading to land). The international project DATAMAN (http://www.dataman.co.nz) aims to

Abbreviations: DM, dry matter; EF, emission factor; EU, European Union; FW, fresh weight; GHG, greenhouse gas; TAN, total ammoniacal nitrogen; VS, volatile solids.

develop a global database on greenhouse gases (N_2O, CH_4) and NH_3 emissions from the manure management chain to refine emission factors (EFs) for national greenhouse gas and NH_3 inventories. This paper describes the housing and outdoor storage components of this database. Relevant information for different animal categories, manure types, livestock buildings, outdoor storage, and climatic conditions was collated from published peer reviewed research, conference papers, and existing databases published between 1995 and 2021. In the housing database, 2024 EFs were collated (63% for NH_3, 19.5% for CH_4, and 17.5% for N_2O). The storage database contains 654 NH_3 EFs from 16 countries, 243 CH_4 EFs from 13 countries, and 421 N_2O EFs from 17 countries. Across all gases, dairy cattle and swine production in temperate climate zones are the most represented animal and climate categories. As for the housing database, the number of EFs for the tropical climate zone is underrepresented. The DATAMAN database can be used for the refinement of national inventories and better assessment of the cost-effectiveness of a range of mitigation strategies.

1 | INTRODUCTION

The agriculture, forestry, and other land use sector accounts for about 24% of global greenhouse gas (GHG) emissions (IPCC, 2014). Of this, about half is contributed by agriculture, especially by livestock agriculture (Reisinger & Clark, 2018). According to Gerber et al. (2013), enteric fermentation accounts for 44% of total agricultural emissions (~3.5 gigatonnes CO_2-eq), and manure management accounts for about 10% (0.8 Gigatonnes CO_2-eq). Ammonia (NH_3) emissions contribute indirectly to GHG emissions but also play a role in reducing biodiversity (Leip et al., 2015) and human life expectancy because of its contribution to the secondary formation of fine particulate matter ($PM_{2.5}$) (Ma et al., 2021). About 40–49% of the global NH_3 emissions are due to livestock manure (Cai et al., 2021).

There is an urgent need to reduce these harmful emissions, with international agreements setting mandatory targets for the reduction of emissions. Greenhouse gas emissions are regulated under the Kyoto Protocol (UNFCCC, 2022a) and the Paris Agreement (UNFCCC, 2022b). The Paris Agreement has the goal of limiting global warming to well below 2 ˚C, preferably to 1.5 ˚C above preindustrial levels (IPCC, 2018). The long-term strategy of the European Union (EU) is to reach climate neutrality by 2050 (European Commission, 2022).

In reaction to the Paris Agreement, about half of the EU Countries established national climate laws to provide a framework for considerable reductions in GHG emissions (Duwe & Evans, 2020). Many of these climate laws disaggregate the national emission reduction targets to the contributing sectors. In Germany for example, the climate package that consists of the Climate Action Law and the Climate Action Plan 2050 requires the agricultural sector to reduce emissions in 2030 by 17% compared with 2020 (BMUB, 2016). It is the first time that the agricultural sector has faced specific and mandatory GHG reduction targets, which greatly increases the pressure on agriculture to reduce GHG emissions and to implement a reporting method that verifies reduction targets have been reached.

In addition to the global GHG reduction efforts, most European countries are committed to reduce a range of air pollutants, with the decrease in NH_3 emissions the most relevant for the agricultural sector. The Convention on Long-Range Transboundary Air Pollution (UNECE, 1979) was established in 1979 and has since been extended by eight protocols. Agricultural NH_3 emissions are regulated under the "1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol)," last updated in 2019 (UNECE, 2022). These internationally binding regulations are accompanied by mandatory methodologies to estimate and report emissions. Achievements in the reduction of GHG and NH_3 emissions from agriculture are compiled in national emission inventory reports. These must be consistent, comparable, complete, accurate, and transparent. Amon et al. (2021) give an overview in the development of emission reporting methods and assess the influence of the method on the inventory reporting.

In general, emissions are estimated by multiplying "activity data," here meaning quantitative estimates of manure nitrogen (N) or manure volatile solids (VS) managed by specific agricultural practices with emission factors (EFs), which represent the proportion of manure N or VS lost as gaseous N (N_2O or NH_3) or gaseous C (CH_4) to the atmosphere (IPCC, 2006). Inventory reporting is categorized into three Tiers, depending on the level of detail included in the emission estimates (IPCC, 2006). The least detailed method, Tier 1, applies default values for EFs for each animal subcategory. Here, no differentiation in management options or country-specific data is possible. The Tier 2 approach includes more details and can make use of country-specific information and manure management systems. The most sophisticated approach, Tier 3, uses more complex models for the estimations, enabling the effect of mitigation measures to be taken into account.

The establishment of EFs must take into account a range of key influencing factors, such as animal performance, housing system, manure treatment, etc. Identification and implementation of effective mitigation measures require relationships between key influencing factors and resulting emissions to be established. Despite the abundance of animal housing and outdoor manure storage emission measurements that have been carried out around the globe in the last decades, there is still considerable uncertainty about which factors have the largest influence on gaseous emissions (Petersen at al., 2018). The development of a database of all relevant published emission values on the manure management chain could help to improve the models and to address questions about the influencing factors. In addition, it would allow the refinement of emission factors for different livestock systems and climate zones. Improving knowledge of effluent emissions from housing and storage is not only an environmental issue; it is also an important resource from an agronomic and economic point of view. The DATAMAN project has enabled the development of this database that contains information from studies on CH_4, N_2O, and NH_3 emissions from livestock housing, grazing, and outdoor storage and field application of manure (Beltran et al., 2021; van der Weerden et al., 2021). It has global scope and was compiled and quality controlled by an international team of experts.

The objective of the current study was to describe the housing and outdoor storage–based component of the DATAMAN database, with a specific focus on CH_4, N_2O, and NH_3 EFs for animal housing and manure storage from countries where these livestock farming systems are practiced.

Core Ideas

- Livestock manure management systems are one of the main sources of greenhouse gas and ammonia emissions worldwide.
- We built a database of CH_4, NH_3, and N_2O emissions from livestock housing and outdoor manure storage.
- The housing database contains 392, 1,281, and 351 emission factors for CH_4, NH_3, and N_2O, respectively.
- The storage database contains 243, 654, and 421 emission factors for CH_4, NH_3, and N_2O, respectively.
- Due to the lack of studies, not all regions of the world are in the database.

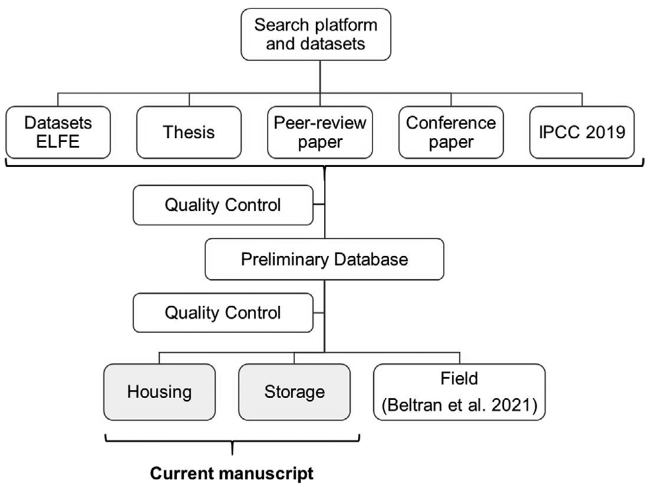

FIGURE 1 Summary of process for collating data of DATAMAN database and the focus of the current paper. ELFE, ELevage et Facteurs d'Emission (Vigan et al., 2019)

2 | MATERIALS AND METHODS

2.1 | Process of data collection

Data collection (Figure 1) was carried out by partners of the MELS (Mitigating Emissions from Livestock Systems; https://www.mels-project.eu/) and DATAMAN (http://www.dataman.co.nz; link to the project's database) consortia from September 2018 to May 2021. During this time, information on CH_4, N_2O, and NH_3 emissions from animal housing (cattle, swine, and poultry) and outdoor manure storage was sourced from published peer-reviewed research, theses (undergraduate and postgraduate), and conference papers. Data collation covered 24 countries for animal housing and 20 for storage.

Searches were performed using a range of Web-based platforms including Web of Science, ScienceDirect, Scielo, and Google Scholar. Keywords in English, Spanish, and Portuguese included four search terms: (a) manure type (solid manure, deep litter, farmyard manure, slurry, manure, broiler litter, liquid fraction, solid fraction, digestate, compost, dropping); (b) animal (dairy cattle, beef cattle, swine, broiler, laying hen, poultry); (c) gas (N_2O, NH_3, CH_4); and (d) animal housing, manure storage, animal building, barn, and outdoor storage.

In addition to data collected from peer-reviewed research, the database includes information extracted from existing datasets, such as ELFE (ELevage et Facteurs d'Emission; Vigan et al., 2019), data collated in connection with the 2019 refinement of the 2006 IPCC guidelines (IPCC, 2019), reviews (e.g., Kupper et al., 2020), and many individual studies not captured in reviews or existing datasets.

All studies were checked for their suitability for inclusion in the database with the following criteria: (a) laboratory, pilot, or commercial scale studies conducted for 6 d or more and (b) measurements conducted with one of the following methods: tracer ratio, direct method, micrometeorological methods, or dynamic and static enclosures. We excluded all modeling studies because the focus was to collate only measurement data. Inclusion of relatively short-term or laboratory-scale experiments (for storage) broadens the potential use of the database beyond revised EFs toward identifying key drivers of emission. Data from laboratory-scale experiments were included in the assessment of EFs.

The major objectives of the DATAMAN project were to determine revised EFs and assess key drivers of emissions. Data in the scientific reports accessed were typically entered as rates of emission or cumulative emissions, with a wide range of units used. Consequently, additional work was required to either derive or estimate EFs using the information provided in a publication (derived) or using national data (estimated), where key information was omitted (e.g., average kg N excretion per lactating dairy cow). This methodology, which was developed for the data conversion to EFs, can be found in Webb et al. (2021) and will not be discussed here. The housing and storage databases identify EFs in terms of whether they were supplied in the report, derived from data in the report, or estimated from data in the report and national default values. However, it was not possible to apply this methodology to all reported emission values due to insufficient key information (e.g., the surface of storage, the number of animals) in the related papers; these emission values (rates and cumulative emissions) are not included in the tables and figures given in the current paper because it deals solely with EFs.

2.2 | Description of variables included in the housing and storage databases

Housing and storage data were collated using templates developed in Microsoft Excel. The housing and the storage templates included 163 and 146 variables, respectively, which were grouped into different categories: "General," "Gas Measurement," "Animal Description," "Manure Description," "Climate," "Data Conversion," and "Housing Description" (the latter was limited to the housing template). The nature (qualitative or quantitative) of each variable varies in function. For example, some variables describe the methodology and treatments used in individual studies, whereas other variables relate to the measured data reported by individual studies. All these variables are presented and defined in the Glossary/Units section of the website that supports the database (https://dataman.co.nz/DataManGlossaries). Furthermore, the Web-based database includes a filtering function based on some of the key variables listed below, allowing users to examine and download subsets of the entire database.

The "General" category is the only category that is identical in both templates. It contained 21 variables, including trial description, country, research institute that conducted the study, replicate number, latitude, longitude, database identification, online link to published research paper, reference of research paper, degree of variation in reported EF means, statistical method used to determine EF means, comments, and experiment identification.

The "Gas Measurement" category contained 24 variables in the housing template and 21 variables in thee storage template, including gas measured, emission measurement technique, start and end times of gas measurements, measurement duration, number of measurements, cumulative emission, emission rate, and EF (supplied, estimated, or derived). Measurement techniques focus on the general measurement approach.

The "Animal" category contained 42 variables in the housing template and 26 variables in the storage template, including animal category and subcategory, animal breed, number of animals, and animal feeding. Animal categories included cattle, dairy cattle, beef cattle, swine, poultry, sheep, and goat. "Cattle" is available as an option for occasions when reports did not specify whether beef cattle or dairy cattle were studied. Many variables concerning animal feeding composition and milk production have been aligned with the CEDERS (Capturing the Effects of Diet on Emissions from Ruminant Systems) project (https://globalresearchalliance.org/wp-content/uploads/2018/06/15-CEDERS_Alex-Hristov.pdf). In the housing template, the number of variables concerning animal feeding is higher than those for the storage (23 vs. 18) to provide data compilers with the option to capture the chemical and nutritional characteristics of up to two different feeds to take into account biphasic feeding. Variables concerning animal categories, animal growth, and breeding conditions are also given in the housing template.

The "Manure" category contained 44 and 59 variables for housing and storage templates, respectively, including manure type, manure chemical composition (e.g., dry matter content [DM], total N concentration, total ammoniacal N concentration [TAN], VS, ash content, C/N ratio, pH), manure treatment, and duration of storage. For housing, additional variables concerning C and N animal excretion and manure management (e.g., removal, drying, use of additives, composting) were also included. For the storage template, storage conditions have been captured using variables such as storage type, storage facility dimension, and manure volume and weight at start and end of storage. The "manure treatment" variable for storage referred to possible treatment of solid or liquid manure (e.g., covering, compaction, aerobic treatment, solid separation, anaerobic digestion, composting, acidification, and the use of urease and/or nitrification inhibitors).

We consulted the RAMIRAN glossary (Pain & Menzi, 2011) for guidance on definitions of manure type and storage type and included relevant descriptions in the Glossary/Units section of the database.

"Climate" contains three variables for housing and 13 for storage. The common variables are climate zone, air relative humidity, and average wind speed during the trial. Climate zone was divided into four categories: temperate wet, temperate dry, tropical wet, and tropical dry, as defined by Beltran et al. (2021). Other variables, such as the mean air and manure temperature, wind speed (over first 12 h and 3 d), and variables concerning rainfall (total rainfall during the trial, during the first hour, and during the first 6 h of storage) are requested for storage.

The "Housing" category contains 21 variables (only in the housing template) that mainly concern the description of the house and its equipment (e.g., surface, volume, air scrubber, cooling, ventilation system). Other variables provide an indication of the ambient conditions (e.g., mean housing temperature, humidity, mean duration of lighting per 24 h). As for manure type, the RAMIRAN glossary (Pain & Menzi, 2011) was consulted for definitions of housing types.

The last category, "Data Conversion," concerns the default values for emission rate/cumulative loss unit conversion for derived or estimated EFs. The templates contain seven and five variables for housing and storage templates, respectively. For housing, these variables are the annual and daily excretion of N and VS and for storage the N and VS content of the manure and the proportion of total N as TAN. Both templates have a default value concerning animal weight.

All variables were selected based on the variables included in the ELFE database and expert judgment of DATAMAN researchers, building on earlier informal discussions between members of the Global Research Alliance Manure Management Network. No single study had the full suite of variables available.

2.3 | Quality control entry process

The data obtained from existing databases (ELFE & IPCC refinement) had already undergone a quality control process when they were collated (Vigan et al., 2019; Kupper et al., 2020; IPCC, 2019; B. Amon, personal communication, 14 June 2021). Nevertheless, for other inputs, and to check the consistency of the whole database, four different approaches were implemented for the quality control: (a) The collected variables are of the type character, integer, or numeric. To guide data compilers and provide an easy first-step visual quality control check, for many numeric or integer variables, a value range was given based on experts' judgement. For variables of type character, the maximum length of the expected string has been indicated. We also included dropdown lists for some character variables to homogenize the terms used to simplify the quality control process and facilitate the use of the collated information. (b) Data were checked for duplication, which could occur due to the incorporation of existing datasets and collation of data from individual studies. (c) A graphical and tabular visualization of some of the numeric variables made it possible to identify outliers, which were then compared with the original studies to confirm their validity. (d) Consistency concerning selection of manure type and treatment were checked.

3 | MAJOR CHARACTERISTICS OF THE DATASET

3.1 | Housing dataset

3.1.1 | Summary of database per country, continent, and climate zone

A higher number of EFs was observed for the housing database (Table 1; Figure 2) than the storage dataset, with 392, 1,281, and 351 EFs for CH_4, NH_3, and N_2O, respectively.

Europe is the continent with the most EFs in the database (71, 68, and 79% of the total number of Efs for CH_4, NH_3, and N_2O, respectively). In Europe, EFs come from 18 countries spread over the whole continent. Ammonia is the most frequently observed gas with 875 EFs; 24% comes from France, 13% from The Netherlands, 16% from the United Kingdom, and 12% from Belgium. Most countries have data for all three gases, except for the Czech Republic, Ireland, Lithuania, Slovenia, and the United Kingdom, which only have NH_3 data for housing studies. The total number of EFs for N_2O and CH_4 is similar (276 and 278), with high differences between countries for both gases; the number of EFs for N_2O varies from 87 (for France) to 1 (for Germany) and from 77 (for Belgium) to 2 (for Hungary) for CH_4. The total number of EFs cannot be related to the total livestock population by country. For example, Germany has a higher livestock population than Belgium (11 million vs. 2.3 million live bovine animals [Eurostat, 2022]) but a much lower number of EFs; for all gases combined there are 50 vs. 261 for Germany and Belgium, respectively. For some countries with high ruminant livestock

TABLE 1 Summary of the database for CH_4, NH_3, and N_2O emission factors for animal housing

Continent	Country	Number of emission factors		
		CH_4	NH_3	N_2O
Europe	Austria	10	10	18
	Belgium	77	107	77
	Czech Republic	0	11	0
	Denmark	33	51	29
	France	43	212	87
	Germany	22	27	1
	Hungary	2	2	0
	Ireland	0	37	0
	Italy	25	39	14
	Lithuania	0	6	0
	The Netherlands	14	115	7
	Poland	27	47	18
	Portugal	9	18	15
	Slovenia	0	3	0
	Slovakia	4	18	4
	Spain	6	19	6
	Sweden	6	15	0
	United Kingdom	0	138	0
	Total	278	875	276
North America and South America	Brazil	0	7	1
	Canada	26	55	18
	United States	82	306	47
	Total	108	368	66
Oceania	Australia	6	9	6
	Total	6	9	6
Asia	China	0	24	3
	South Korea	0	5	0
	Total	0	29	3
Grand total		392	1,281	351

populations (e.g., Ireland, United Kingdom, and Brazil), there are no housing CH_4 EFs.

For North America and South America, EFs are available for three countries (Brazil, Canada, and United States), but the majority come from United States (76, 83, and 71% of the total number of EFs for CH_4, NH_3, and N_2O, respectively). Ammonia is also the gas with the highest number of EFs (68% of the total number of EFs for North America and South America). There are no data for CH_4 from Brazil and only one value for N_2O. Emission factors for Oceania and Asia represent <2% of the housing database. For Asia, there are no CH_4 EF data.

These results indicate that countries and continents (example.g., South American and Asia) with a high number of ruminant populations have lower numbers of studies related to EFs for manure storage and housing compared with Europe. Therefore, we encourage researchers and policy maker from these continents to improve the knowledge in these regions.

3.1.2 | Type of animal, housing, and ventilation

The numbers of CH_4, NH_3, and N_2O EFs for housing are summarized based on climate zone, animal, housing, ventilation, manure type, and manure management in Table 2.

Across all gases, the swine category is the most represented, with 210, 694, and 191 EFs for CH_4, NH_3, and N_2O, respectively. In the cattle category, the number of EFs is greater for dairy cattle than for beef cattle: 116 vs. 18 for CH_4, 257 vs. 72 for NH_3, and 97 vs. 17 for N_2O. The higher numbers of EFs for swine than for cattle can be explained by the swine housing generally having a mechanical ventilation system, which simplifies gas measurements, as opposed to cattle housing, which is usually naturally ventilated and more challenging to make measurements from (Calvet et al., 2013; Ogink et al., 2013). This is also confirmed by the number of EFs for which the ventilation system is given, with >75% of the EFs across all gases from buildings with mechanical ventilation. For poultry, the number of EFs is higher for NH_3 (258) than for CH_4 (48) and N_2O (46).

Concerning the type of house, the maximum number of EFs was found for mechanically ventilated houses, such as deep pit or closed houses for swine production. Deep pit houses have the greatest number of EFs for NH_3 ($n = 501$), CH_4 ($n = 127$), and N_2O ($n = 96$). The EFs given for the cubicle house category mainly concern dairy cattle. For NH_3, 27% of EFs are given for cubicle house with forced ventilation and 54% with natural ventilation (the rest is given as "unsure").

For tie stalls, 58% of NH_3 and CH_4 values are for dairy cattle (milking cows) and 41% for beef cattle. For N_2O, 68% of the values are for dairy cattle (milking cows) and 32% for beef cattle (heifers and steers). For poultry, aviary house is the most represented category for NH_3 ($n = 97$), and poultry floor housing is the most represented category for N_2O ($n = 20$) and CH_4 ($n = 14$). Emission factors for poultry floor housing are mainly for broilers (80%).

3.1.3 | Variables collated in the CH_4, NH_3, and N_2O housing dataset

As for manure storage, none of the selected variables for housing was given in all publications. Table 3 presents the number of observations for a selection of quantitative variables relative to the total CH_4, NH_3, and N_2O EFs for housing. Some

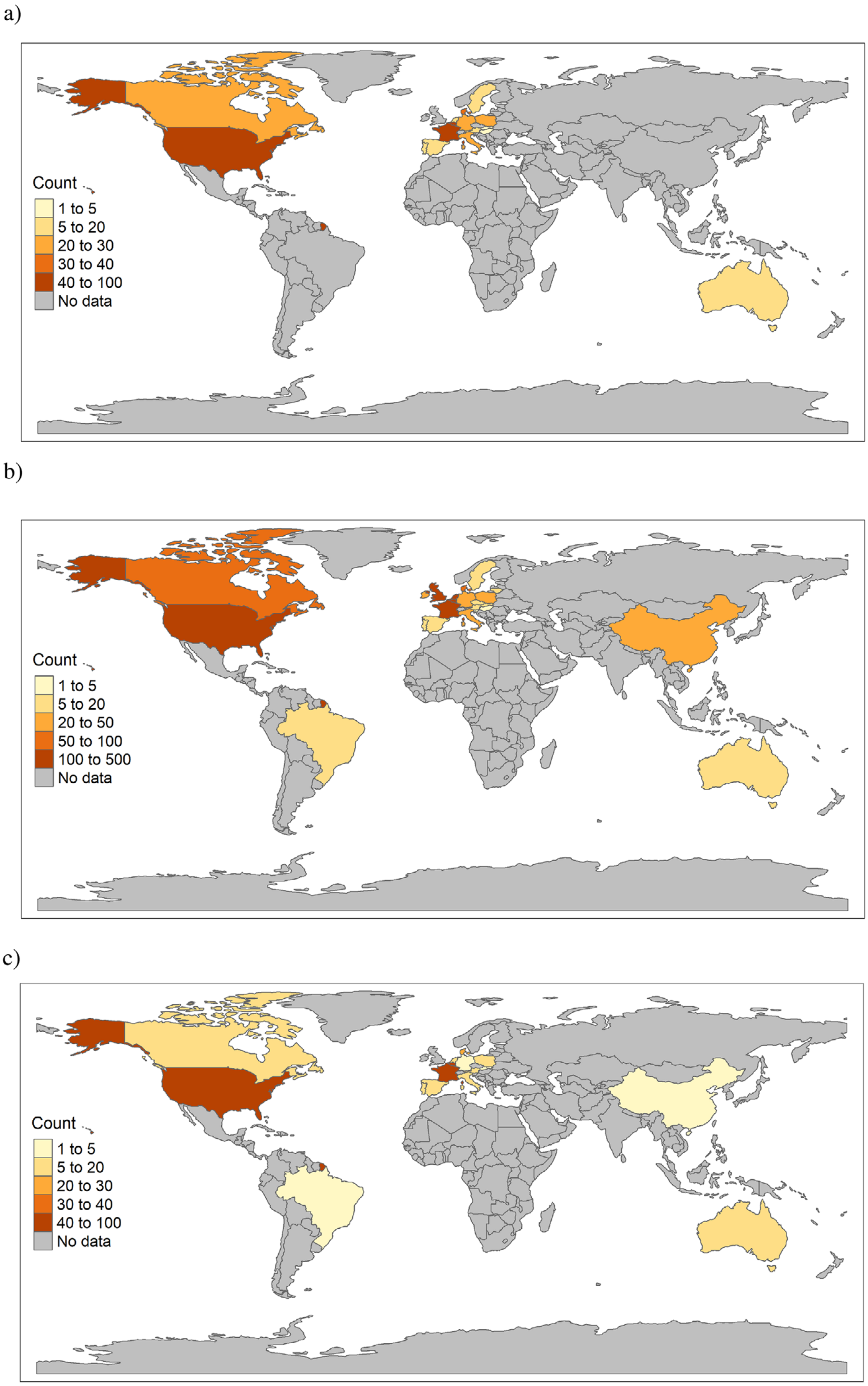

FIGURE 2 Distribution per country for (a) CH_4 emission factors (EFs), (b) NH_3 EFs, and (c) N_2O EFs associated with housing. Scale for NH_3 emission factors differs from that used for N_2O and CH_4

of these variables are known to be key drivers (Philippe et al., 2011; Rigolot et al., 2010); others are useful for deriving EF.

Of the variables presented in Table 3, the "number of animals" is the most widely reported, with >90% of EFs including this information. Average live weight is provided for about one-third of the emission values, regardless of gas type, but the distribution according to animal categories varies between the gases. For CH_4, this variable is provided for 54% of dairy cattle EFs and 32% of swine EFs; for N_2O, this variable is provided for 70% of dairy cattle EFs and 11% of swine

TABLE 2 Summary of data collated for CH_4, NH_3, and N_2O emission factors for housing according to climate zone, animal category, housing type, ventilation type, manure type, and manure treatment

Variables	Number of emission factors		
	CH_4	NH_3	N_2O
Climate zone			
Temperate dry	14	29	12
Temperate wet	378	1,245	338
Tropical dry	0	7	1
Tropical wet	0	0	0
Animal category			
Beef cattle	18	72	17
Dairy cattle	116	257	97
Poultry	48	258	46
Swine	210	694	191
House			
Aviary house	5	97	2
Battery cage house	5	14	3
Closed house	76	106	73
Cubicle housing	73	157	47
Deep pit house	127	501	96
Enriched cages	12	14	6
Feedlot	0	16	1
Kennel house	2	2	2
Loose housing	24	85	40
Open lot	11	13	10
Poultry floor housing	14	80	20
Tied stalls	29	87	37
Unsure	14	109	14
Ventilation			
Forced	292	905	251
Natural	89	189	80
Natural and forced	1	14	0
Natural and forced in the pit	2	2	0
Unsure	8	171	20
Manure type			
Broiler litter	13	98	23
Layer manure	16	107	12
Slurry	206	621	149
Solid manure	138	249	146
Unsure	19	196	21
Manure management			
Additives–chemical	3	6	6
Additives–unknown	1	1	1
Composted	0	2	0
None	34	105	17
Other	13	14	11
Removed	0	6	3
Separation system	14	16	13

EFs, and for NH_3 this variable is provided for 33% of dairy cattle EFs and 52% of swine EFs. Concerning "average daily gain," >80% of the given values are for the swine category (data not shown). The variables C and N excreted are seldom included in published studies, which can make it difficult to derive EFs from the reported gas measurements when the EFs are not included in publications (Webb et al., 2021). Feed crude protein can be used to estimate N excretion for certain animal categories; however, this variable is also seldom reported. Data on "measurement duration" are important for evaluating the representativeness of the measured emissions over the rearing period. This information is provided for 71, 53, and 67% of the EFs for CH_4, NH_3, and N_2O, respectively.

Key variables (e.g., egg or milk production) specific to certain livestock systems and useful for unit conversion were also collated in papers. Although the number of EFs for laying hens is low for all gases (26 for CH_4, 148 for NH_3, and 18 for N_2O; data not shown), the number of occasions with the variable "egg production" is low (3 for CH_4, 22 for NH_3, and 3 for N_2O). This contrasts with dairy cattle "milk production" data, which are provided more regularly, with 101 of the 116 CH_4 EFs, 133 of the 225 NH_3 EFs, and 82 of the 97 N_2O EFs.

3.1.4 | Frequency and distribution of variables

For N_2O, EFs vary between 0 and 24.3% of excreted N ($N_{excreted}$), with 87 values <0.2% of $N_{excreted}$ and 261 <1.4% of $N_{excreted}$. Seventy-six percent of the highest values are for swine; the rest are mainly for beef cattle and dairy cattle (only two values for poultry), and 57% are for solid manure (Figure 3).

For CH_4, the EFs range between 0 and 62.2% of excreted VS ($VS_{excreted}$). There are 97 values with <1.1% of $VS_{excreted}$ and 282 with <7.4% of $VS_{excreted}$. Beef cattle and dairy cows represent 67% of the highest values; the remaining mainly refer to swine. However, even though for housing the EFs include both enteric and manure CH_4 measurements, the highest EFs do not all relate to cattle because in this case they were expressed as percentage of $VS_{excreted}$.

For NH_3, EFs are between 0 and 76.8% of $N_{excreted}$, with 319 values <5.8% of $N_{excreted}$ and 959 <20.2% of $N_{excreted}$. For the 322 values >20.2% of $N_{excreted}$, 224 are for swine (64 with solid manure and 117 with slurry), 51 for poultry (25 for

TABLE 3 Number of observations for a selection of quantitative variables relative to the total CH_4, NH_3, and N_2O emission factors for housing

Variables	Number of values (in % of the total number of values for each gas)		
	CH_4 (n = 392)[a]	NH_3 (n = 1,281)	N_2O (n = 351)
Number of animals	92	91	94
Average live weight, kg liveweight head^{-1}	36	27	29
Average daily gain, kg liveweight gain head^{-1} d^{-1}	34	26	46
Excreted C, g animal^{-1} d^{-1}	0	0	1
Excreted N, g animal^{-1} d^{-1}	11	12	10
Feed crude protein content, % of DM	19	10	22
Manure total N, kg t^{-1} FW	26	17	26
Measurement duration, d	71	53	67

Note. DM, dry matter; FW, fresh weight.

[a]Total number of emission factors.

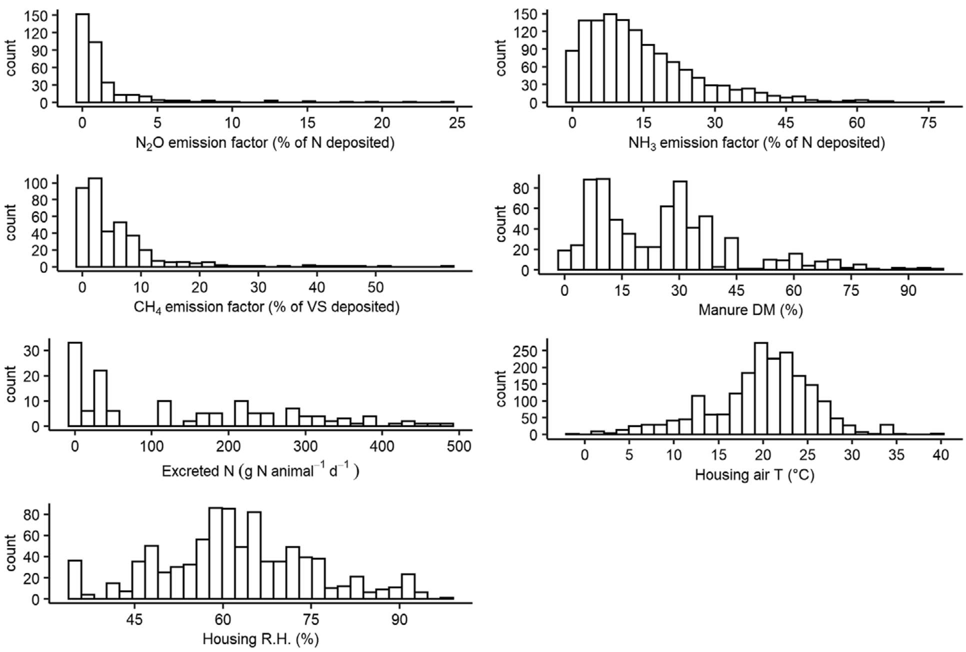

FIGURE 3 Histogram of emission factors, manure and climate variables for all manure type included in the N_2O, NH_3, and CH_4 housing datasets. The y axis shows frequency (count). Manure DM, manure dry matter; R.H., relative humidity; T, temperature

broilers, 20 for layers), and 47 are for beef and dairy cattle (with 21 values for solid manure).

Manure DM concentration varies between 0 and 97.4%, with 522 values having DM of <34%. Excreted N expressed as g animal^{-1} d^{-1} range between 0.98 and 485, with the lower value relating to broilers and the highest values relating to dairy cattle. Concerning climatic conditions, housing air temperature ranges between −1 ˚C (only one value observed in Poland in a cattle barn [Angrecka & Herbut, 2014]) and 40 ˚C (two values in the United States for swine [Harper et al., 2001]), and housing relative humidity ranges between 34 and 97%.

3.2 | Storage dataset

3.2.1 | Summary of database per country and continent

Table 4 and Figure 4 present a summary of the storage database, which contains 243, 654, and 421 EFs for CH_4, NH_3, and N_2O, respectively.

Europe is the continent with the most EFs for all gases (110 for CH_4, 414 for NH_3, and 199 for N_2O). In North America, NH_3 is the most represented gas, probably because of North American regulations limiting NH_3 emissions for some farm categories (Bjerg et al., 2019) and the implementation of

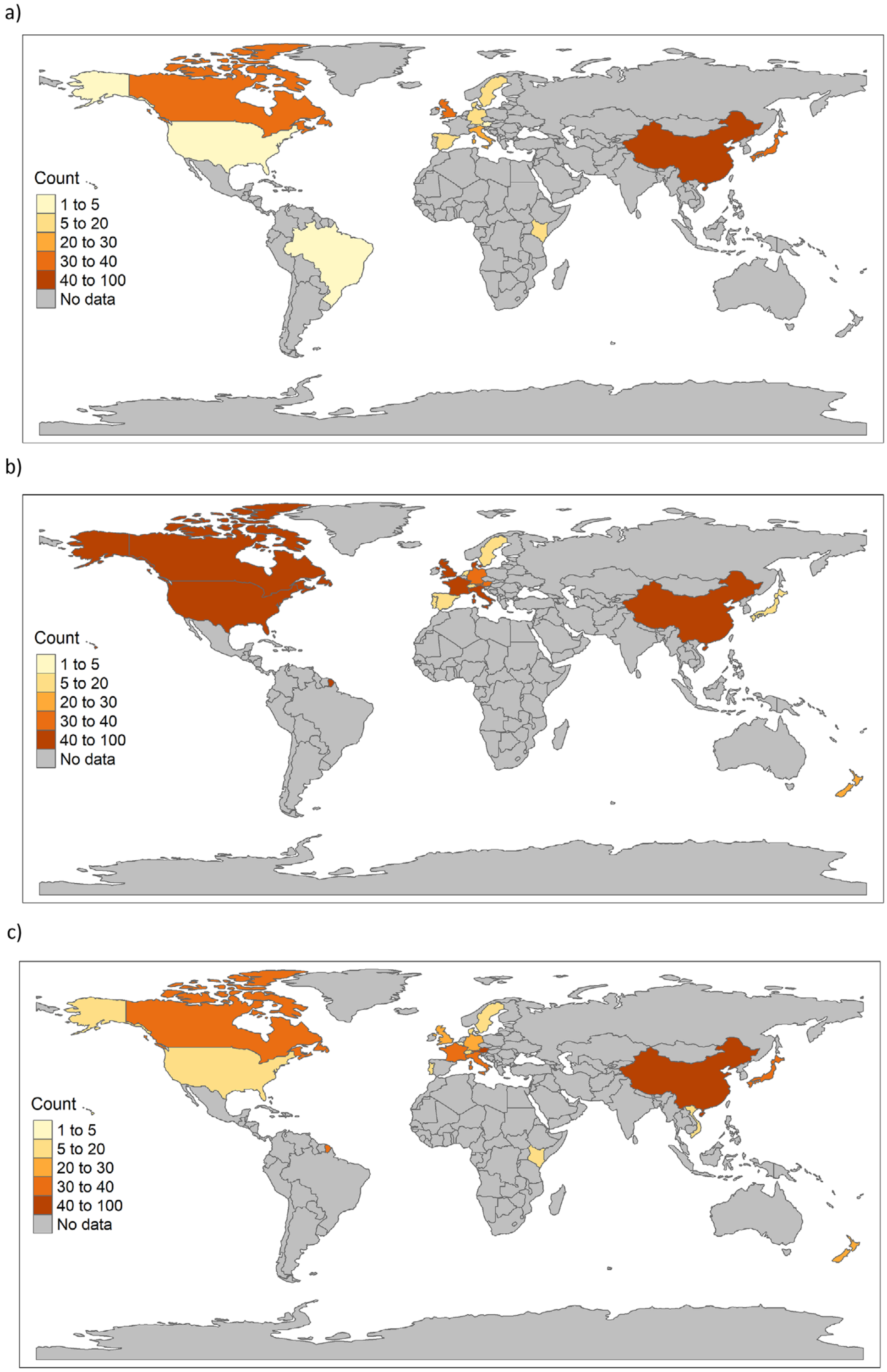

FIGURE 4 Distribution per country for (a) CH_4 emission factors (EFs), (b) NH_3 EFs, and (c) N_2O EFs, associated with outdoor storage of manure

mitigation techniques (Santonja et al., 2017). Ammonia EFs were collated from 16 countries (though unfortunately none from African countries), CH_4 EFs from 13 countries, and N_2O EFs from 17 countries in all continents. In Africa and Oceania, the EFs were collated from only one country (Kenya and New Zealand, respectively). In North America and South America, most GHG studies were conducted in Canada. For Asia, EFs were obtained from three countries (China, Japan, and Vietnam), with the majority from studies conducted in China (71%), followed by Japan (26%).

TABLE 4 Summary of the database for CH_4, NH_3, and N_2O emission factors for outdoor manure storage

Continent	Country	Number of emission factors		
		CH_4	NH_3	N_2O
Europe	Austria	3	37	40
	Belgium	0	0	2
	Denmark	8	57	12
	France	0	46	36
	Germany	18	36	24
	Italy	24	91	31
	The Netherlands	0	10	0
	Portugal	0	8	8
	Spain	8	17	0
	Sweden	11	6	12
	Switzerland	0	6	12
	United Kingdom	38	100	22
	Total	110	414	199
North America and South America	Brazil	1	0	0
	Canada	35	51	36
	United States	4	70	10
	Total	40	121	46
Oceania	New Zealand	0	28	28
	Total	0	28	28
Africa	Kenya	6	0	6
	Total	6	0	6
Asia	China	54	76	98
	Japan	33	15	36
	Vietnam	0	0	8
	Total	87	91	142
Grand total		243	654	421

3.2.2 | Type of animal and manure

The number of CH_4, NH_3, and N_2O EFs for manure storage were disaggregated by climate zone, animal, manure type, manure treatment, and storage type (Table 5). For all gases, dairy cattle and swine are the most represented animal categories. Dairy cattle represent 37% of the CH_4 dataset, 22% of the NH_3 dataset, and 35% of the N_2O. Swine represent 39% of the CH_4 dataset, 48% of the NH_3 dataset, and 32% of the N_2O dataset. The cattle category is also well represented for all three gases, with 12, 19, and 17% of the total number of CH_4, NH_3, and N_2O EFs, respectively. Poultry represent about 10% of the EFs for the three gases, whereas other animal categories represented only a small percentage. Regarding manure type, slurry was the most common manure type for NH_3 and CH_4 (60 and 48% of the EFs, respectively), whereas solid manure was the most common

TABLE 5 Summary of data collated for CH_4, NH_3, and N_2O emission factors for storage according to climate zone, animal type, manure type, manure treatment, storage type

Variables	Number of emission factors		
	CH_4	NH_3	N_2O
Climate zone			
Temperate dry	15	31	53
Temperate wet	221	623	362
Tropical dry	6	0	6
Tropical wet	1	0	0
Animal			
Beef cattle	8	14	19
Cattle	29	125	72
Dairy cattle	89	142	149
Poultry	22	62	45
Swine	95	311	136
Manure type			
Broiler litter	0	20	17
Composted manure	2	3	3
Digestate	9	31	25
Digested separated liquid	6	6	12
Digested separated solid	6	6	6
Dirty water	13	8	18
Layer manure	22	42	28
Separated liquid	6	9	3
Separated solid	6	9	4
Slurry	116	390	133
Solid manure	57	130	172
Manure treatment			
Acidification in house	0	6	0
Acidified	15	19	10
Aerobic treatment	14	5	13
Compacted	0	6	5
Composted	68	93	135
Covered	22	147	67
Drying	3	3	3
None	89	145	85
Other	0	9	0
Solid separation	0	17	13
Unsure	30	204	91
Manure storage type			
Experimental vessels	27	36	25
Lagoon	0	57	0
Manure heap	42	104	114
Pit	11	32	19
Slurry tank	90	238	123

(Continues)

TABLE 5 (Continued)

Variables	Number of emission factors CH_4	NH_3	N_2O
Unsure	73	198	138
Weeping-wall	0	3	3

manure type for N_2O, representing 32% of the EFs. For N_2O, solid manure is the category that has the most EFs (41%) (Table 5).

3.2.3 | Manure treatment and storage type

For CH_4, 28% of the EFs concern composted manure, 9% are from storage facilities with a cover, and 37% are from manure with no treatment or cover. For NH_3 and N_2O, 14 and 32% of the EFs are from composting, and 22 and 16% are from covered outdoor storage, respectively. The category "unsure" is not negligible irrespective of the gas measured (12% for CH_4, 31% for NH_3, and 22% for N_2O), whereas the "other" treatment represents only a few EFs (<1% of total).

The most cited storage type is the slurry tank for the three gases. Manure heap represented 17, 16, and 27% of CH_4, NH_3, and N_2O EFs, respectively. The "unsure" category is the dominant one for N_2O (around 33%) and a little lower for CH_4 and NH_3 but considerably high compared with other types of storage (30 and 28%, respectively).

3.2.4 | Variables collated in storage dataset

Table 6 shows the occurrence of some selected variables (e.g., manure pH, TAN content, wind speed, or air temperature) because they are known as parameters influencing emissions (Pedersen et al., 2021; Sommer et al., 2017) or useful for the conversion of emission data into EFs (Webb et al., 2021).

None of the selected variables is given in all publications. Overall, the variables corresponding to manure characteristics were more commonly reported for slurry than for solid manure. However, for the N_2O dataset, the total N, organic C, C/N ratio, and DM were more commonly reported in publications relating to solid manure than for slurry (data not shown). The most reported variables were manure DM, total N concentration, and pH (at the beginning of trials). Manure VS was provided with 43% of CH_4 EFs (64% of these values concern slurry) but only with 21 and 11% of NH_3 and N_2O EFs, respectively. The number of values for CH_4 is higher because VS concentration is a key parameter for CH_4 emissions (Wang et al., 2020).

Average temperature, wind speed, storage facility, fouled surface area, and manure volume relate to the experimental conditions during measurement. These variables were reported for <60% of the EFs. Indeed, there were no wind speed data reported for the entire trial for any study. The same was true for the other two wind speed variables in the datasets: average wind speed over the first 12 h and average wind speed over the first 3 d. For the manure volume, this variable could be estimated by referring to the total storage volume of the storage facility, which is assumed to be given by authors as an indication of the stored volume during the experiments. There was a larger number of studies that reported storage volume than the number of studies that reported manure volume.

3.2.5 | Frequency and distribution of variables

For N_2O, EFs vary between −0.1 and 9.5% of stored manure N (N_{stored}), with 106 values <0.04% of N_{stored} and 316 values <1.2% of N_{stored} (Figure 5). For solid manure, 59% of values were >1.2% of N_{stored} and 17% for slurry; the remaining proportion was shared among the other categories of manure. For solid manure, only seven values are >4%. The lowest and negative N_2O EF corresponds to swine slurry stored in a covered tank in Sweden (Rodhe et al., 2012).

For CH_4, the observations range between 0 and 32.8% of stored manure VS (VS_{stored}), and 78 values are <0.2% of VS_{stored} and 60 >2.1% of VS_{stored}. Slurry is the manure category with the highest number of CH_4 EF and has 43 >2.1% of VS_{stored} with a maximum value of 32.8% of VS_{stored} for dairy slurry tank with a natural crust (Wood et al., 2012). For nine of the values >2.1% of VS_{stored}, the slurry tank was covered.

For NH_3, EFs were between 0 and 84.24% of N_{stored}. In this case, 161 values are below 1.4% of N_{stored} and 483 below 16.8% of N_{stored}. Seventy values exceed 30% of N_{stored}, with an equivalent distribution between the three main animal species, with 22 values from the same study (Termeer, 1993). Three values are >60% and correspond to different studies.

Concerning the chemical characteristics of manure, the DM content varies between 0.07 and 91.7%. For solid manure, values range from 15 to 91.7%, with 12 of the values >60% coming from a single study examining the effect of different bedding materials on NH_3 emissions (Andersson, 1996). Slurry DM concentration ranges between 0.07 and 26% and layer manure between 24.7 and 50.6%. Manure VS values range between 2 and 197 kg VS t^{-1} FW and organic C content between 0.18 and 233 kg C t^{-1} fresh weight (FW). Manure N concentration ranges from 0.04 to 35.8 kg of N t^{-1} FW, and TAN concentration ranges from 0 to 26.2 kg of N t^{-1} FW. Manure pH varies between 4.5 and 10.7 and C/N ratio between 4 and 71, with most values >30 sourced from four studies (Andersson, 1996; Chen et al., 2018; Kierończyk,

TABLE 6 Number of observations for a selection of variables relative to the total CH_4, NH_3, and N_2O emission factors

Variables	Number of values (in % of the total number of values for each gas)		
	CH_4 (n = 243)[a]	NH_3 (n = 654)	N_2O (n = 421)
Manure volume, m^3	36	31	33
Manure mean temperature, ˚C	60	44	38
Storage facility, fouled surface area, m^2	53	56	43
Average air temperature, entire trial, ˚C	41	35	24
Average wind speed, entire trial, m s^{-1}	0	0	0
Measurement duration, d	95	87	83
Duration of storage, d	62	51	52
Manure pH	69	68	59
Manure TAN, kg t^{-1} FW	57	60	45
Manure total N, kg t^{-1} FW	74	66	65
Manure organic C, kg t^{-1} FW	26	19	37
Manure C/N ratio	20	19	34
Manure DM, %	86	69	74
Manure volatile solids, g kg^{-1}	43	21	11

Note. All manure data are for the start of experiment. DM, dry matter; FW, fresh weight; TAN, total ammoniacal N.
[a]Total number of emission factors.

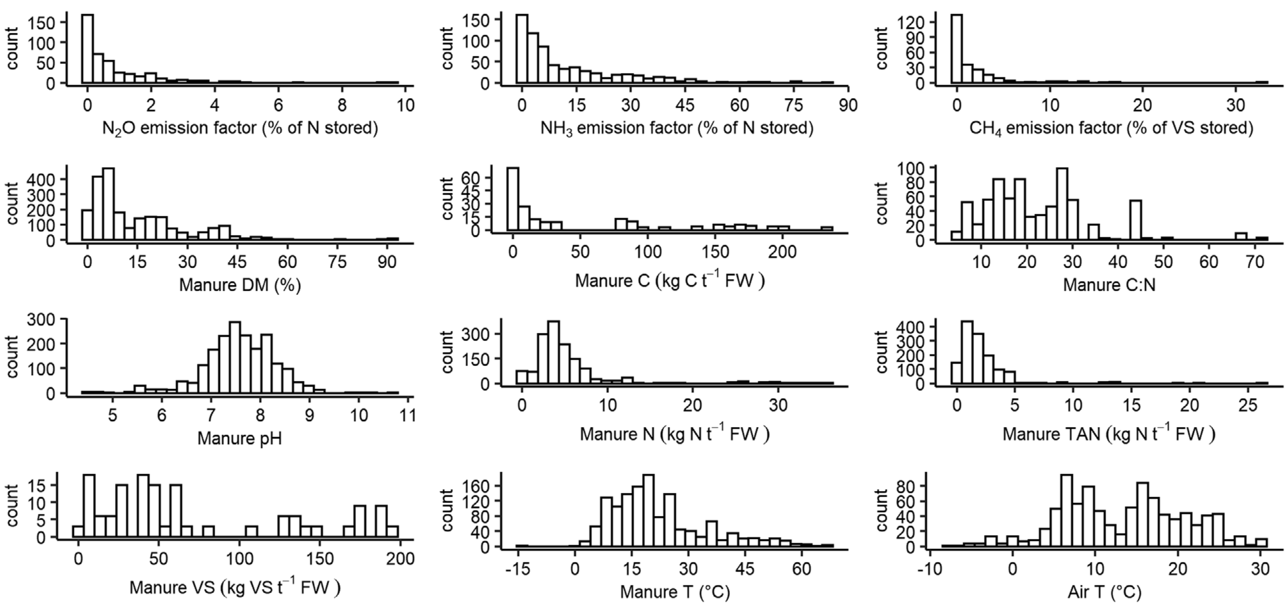

FIGURE 5 Histogram of emission factors (EFs), manure, and climate variables for all manure types included in the N_2O, NH_3, and CH_4 storage datasets. The *y* axis shows frequency (count). For the CH_4 EF a single high value of 92% is not represented on the histogram to make it more legible. For C/N ratio, nine values >100 (three of each of ratios 162, 483, and 607) are not represented on the histogram to make it more legible. Refer to Table 6 for descriptions of abbreviations. Manure C, manure organic C; T, temperature

2014; van der Weerden et al., 2014). Average air temperature measured during the studies ranges from −8 to 30 ˚C. Twenty-eight EFs (1 for N_2O, 3 for CH_4, and 24 for NH_3) correspond to studies with negative average air temperature and 196 with average air temperatures above 20 ˚C, mainly in temperate wet climatic zones. For manure temperature, only two EFs correspond to a negative temperature (both at −13.2 ˚C). High manure temperatures (between 40 and 67.5 ˚C) relating to a study on solid manure are likely to be due to microbial activity in the manure heaps (Miyatake & Iwabuchi et al., 2006).

Although the database has undergone a data entry quality control process, it is important to note that there are uncertainties in the measurements that can result in outliers in EFs and some variables. These uncertainties cannot be easily identified and addressed with the information given in the Material and Methods sections of individual papers. Therefore, data (and more specifically outliers) should be critically evaluated before use.

4 | IMPLICATIONS OF THE DATABASE

This database was created with the aim of providing a central data repository for refining the EFs for the different animal categories according to the farming conditions. These EFs can then be used by different stakeholders to improve the accuracy of national inventories, perform environmental assessments, identify and quantify mitigation techniques, and prioritize influencing parameters. Through the collation of data from studies across the globe, this project has also highlighted the lack of studies in some important livestock production areas and the research needed to explore the standardization of future study approaches and harmonization of data from existing studies.

For both housing and storage databases, the number of EFs from tropical climatic conditions is too small to reliably refine the current IPCC Tier 1 default EFs (IPCC, 2019) for tropical climates. Moreover, for Africa, there are no EFs in the housing database and only six N_2O EFs and six CH_4 EFs (all from Kenya) in the storage database. Reasons for this imbalance in the number of EFs between the different continents may include the availability of adapted measurement methods and variability in livestock systems. The low number of EFs for South America, which is a region with large numbers of high-producing livestock systems, may be due to the primary focus on assessment and mitigation of enteric CH_4 and that most of the cattle production system are grass based.

During the construction of the database templates, many variables were identified for storage and for housing. Some of them are necessary for the characterization of the livestock systems, others for the conversion of the results into reference units such as kg CH_4 kg^{-1} VS stored or % of N excreted, and the majority for the interpretation of EFs. There were no studies that included all variables listed in the database; this is not surprising given that each study had different objectives and therefore had different data requirements. However, to ensure that published gaseous emission measurements can be readily converted to EFs, we encourage researchers to include the reporting of crucial manure and animal variables, as listed by Webb et al. (2021). Some variables, such as N and VS excreted, are also very rarely reported because their determination is often not considered for experiments that focus on emissions from housing-based manure systems. These variables require the implementation of specific protocols that are more likely to be included in experiments dealing with animal nutrition. Concerning CH_4 EFs for housing, most of the collated studies reported CH_4 concentrations within the housing and therefore may have included enteric CH_4 from ruminant livestock (and potentially pigs). Because we were unable to distinguish the source of the CH_4 in these studies, we recommend caution in the application of these data as manure EFs.

This is the first iteration of these two databases, which can be found at www.dataman.co.nz (Version 1.1); however, it is planned to expand these datasets over time, based on the ongoing projects "Mitigating greenhouse gas Emissions from Livestock Systems" (MELS, EraNet Joint Call 2018), "Back to the Future: Reintegrating Land and Livestock for Greenhouse Gas Mitigation and Circularity" (Relive, www.relive-era.net), and "Multi-criteria assessment, decision support and management tools for sustainable circular mixed farming systems for dairy production" (Dairy Mix, www.suscrop.eu/funded-projects/3rd-call/dairymix). The latter two projects were recently selected for funding as part of the EraNet Joint co-fund Call 2021. These projects provide opportunities to improve knowledge of key drivers and data reporting, to develop more detailed EFs for manure sources across different climatic zones and livestock systems, and to evaluate mitigation strategies for the whole manure management chain.

Interested stakeholders are invited to contact the corresponding author of this work for further data contribution to these datasets.

5 | CONCLUSION

The DATAMAN Housing and Storage databases include, respectively, 392 and 243 EFs for CH_4, 1,281 and 654 for NH_3, and 351 and 421 for N_2O published between 1995 and 2021 across different animal categories, different types of manure, livestock buildings, outdoor storage, and climate conditions.

Both databases revealed disparities in the number of available EFs between climatic zones (many more EFs developed for temperate zones than for tropical zones) but also between continents. Although there is a need for continued measurements in all regions of the world with adapted measurement protocols, this need is greatest in poorly represented regions such as Africa, Asia, and South America, where livestock production plays an important role but the number of available EFs is low.

During the MELS project, data will be analyzed to develop revised EFs and generate functional relationships between emissions and activity/ancillary variables, enabling a refinement of national inventories and better assessment of the cost-effectiveness of a range of mitigation measures. The databases will be expanded over time by including new studies on GHG and NH_3 emissions across the world, allowing further refinement and disaggregation of EFs and improving our knowledge of key drivers along the manure management chain.

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AUTHOR CONTRIBUTIONS

Mélynda Hassouna: Conceptualization; Data curation; Formal analysis; Methodology; Resources; Validation; Writing – original draft; Writing – review & editing. Ignacio Beltran: Conceptualization; Formal analysis; Methodology; Resources; Validation; Writing – review & editing. Barbara Amon: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing – original draft. Vasileios Anestis: Formal analysis; Investigation; Resources; Writing – review & editing. Federico Dragoni: Formal analysis; Investigation; Resources; Writing – review & editing. Koki Maeda: Formal analysis; Investigation; Resources; Writing – review & editing. Aristea Maragou: Formal analysis; Investigation; Resources; Writing – review & editing. Tom Misselbrook: Formal analysis; Investigation; Resources; Writing – review & editing. Alasdair D. L. Noble: Formal analysis; Investigation; Resources; Visualization; Writing – review & editing. Anna Rychła: Formal analysis; Investigation; Resources; Writing – review & editing. Priscila Simon: Formal analysis; Investigation; Resources; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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