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REVIEWS AND ANALYSES

Ammonia and nitrous oxide emission factors for excreta deposited by livestock and land-applied manure

Tony J. van der Weerden[1] | **Alasdair Noble**[2] | **Cecile A. M. de Klein**[1] | **Nicholas Hutchings**[3] | **Rachel E. Thorman**[4] | **Marta A. Alfaro**[5] | **Barbara Amon**[6,7] | **Ignacio Beltran**[1,5] | **Peter Grace**[8] | **Mélynda Hassouna**[9] | **Dominika J. Krol**[10] | **April B. Leytem**[11] | **Francisco Salazar**[5] | **Gerard L. Velthof**[12]

[1] AgResearch Ltd, Invermay Agricultural Centre, Mosgiel 9053, New Zealand

[2] AgResearch Ltd, Lincoln Research Centre, Christchurch 8140, New Zealand

[3] Research Centre Foulum, Aarhus Univ., Tjele 8830, Denmark

[4] ADAS, ADAS Boxworth, Battlegate Road, Boxworth, Cambridge CB23 4NN, United Kingdom

[5] Instituto de Investigaciones Agropecuarias (INIA), INIA Remehue, Carretera Panamericana Sur km. 8 Norte, Osorno, Chile

[6] Leibniz-Institut für Agrartechnik und Bioökonomie (ATB), Max-Eyth-Allee 100, Potsdam D-14469, Germany

[7] Faculty of Civil Engineering, Architecture and Environmental Engineering, Univ. of Zielona Gra, Poland

[8] Queensland Univ. of Technology, 2 George St, Brisbane, Queensland 4000, Australia

[9] INRAE, UMR SAS, Rennes F- 35042, France

[10] Teagasc, Environment, Soils and Land-Use Dep., Teagasc, Johnstown Castle, Co., Wexford Y35 TC97, Ireland

[11] USDA-ARS, Northwest Irrigation & Soils Research Lab., Kimberly ID 83341, USA

[12] Wageningen Environmental Research, Wageningen Univ. & Research, P.O. Box 47 AA, Wageningen 6700, The Netherlands

Correspondence
Tony J. van der Weerden, AgResearch Ltd, Invermay Agricultural Centre, Mosgiel 9053, New Zealand.
Email: tony.vanderweerden@agresearch.co.nz

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Abstract

Manure application to land and deposition of urine and dung by grazing animals are major sources of ammonia (NH_3) and nitrous oxide (N_2O) emissions. Using data on NH_3 and N_2O emissions following land-applied manures and excreta deposited during grazing, emission factors (EFs) disaggregated by climate zone were developed, and the effects of mitigation strategies were evaluated. The NH_3 data represent emissions from cattle and swine manures in temperate wet climates, and the N_2O data include cattle, sheep, and swine manure emissions in temperate wet/dry and tropical wet/dry climates. The NH_3 EFs for broadcast cattle solid manure and slurry were 0.03 and 0.24 kg NH_3–N kg^{-1} total N (TN), respectively, whereas the NH_3 EF of broadcast swine slurry was 0.29. Emissions from both cattle and swine slurry were reduced between 46 and 62% with low-emissions application methods. Land application of cattle and swine manure in wet climates had EFs of 0.005 and 0.011 kg N_2O–N kg^{-1}

Abbreviations: DCD, dicyandiamide; DM, dry matter; DMPP, 3,4-dimethyl-1H-pyrazole phosphate; EF, emission factor; GHG, greenhouse gas; TAN, total ammoniacal nitrogen; TN, total nitrogen.

TN, respectively, whereas in dry climates the EF for cattle manure was 0.0031. The N_2O EFs for cattle urine and dung in wet climates were 0.0095 and 0.002 kg N_2O–N kg^{-1} TN, respectively, which were three times greater than for dry climates. The N_2O EFs for sheep urine and dung in wet climates were 0.0043 and 0.0005, respectively. The use of nitrification inhibitors reduced emissions in swine manure, cattle urine/dung, and sheep urine by 45–63%. These enhanced EFs can improve national inventories; however, more data from poorly represented regions (e.g., Asia, Africa, South America) are needed.

1 | INTRODUCTION

Manure application to land and livestock deposition of urine and dung on pasture and rangelands are major sources of ammonia (NH_3) and nitrous oxide (N_2O) emissions from agriculture (Sajeev et al., 2018). Nitrous oxide is a potent greenhouse gas (GHG); livestock systems contribute over 32% of total global N_2O emissions (Uwizeye et al., 2020). Ammonia emissions represent significant losses of nitrogen (N) from agricultural systems and contribute to secondary particulate formation and ecosystem degradation (Behera et al., 2013; Hafner et al., 2018; Sigurdarson et al., 2018). Ammonia volatilization and subsequent downwind deposition onto soil is also an indirect source of N_2O (IPCC, 2006). Livestock production represents 60% of global NH_3 emissions (Uwizeye et al., 2020), largely derived from manure management (Webb et al., 2005).

Manures have traditionally been applied to the entire land surface (e.g., via broadcast application). However, because there can be high losses of NH_3 and odors from broadcast application (Chadwick et al., 2011; Montes et al., 2013), some parts of the world (e.g., Europe) have developed regulatory policies that require lower-emission methods. According to the review by Webb et al. (2010), soil incorporation of slurries and solid manure has shown to be effective in reducing NH_3 emissions by minimizing manure exposure to the air and increasing soil–manure contact. Similar results were reported by Hafner et al. (2018), who modeled reductions of 50 and 70% in NH_3 emissions from cattle slurry applied using a trailing hose and open slot injection, respectively, when compared to broadcast application. Whereas some studies have reported that soil injection of slurry often increases N_2O emissions, other studies have reported similar N_2O emissions between broadcast and manure injection (Chadwick et al., 2011; Webb et al., 2010), suggesting that the effects of manure application method on N_2O emissions depend on the climate conditions that favor (or not) soil denitrification process (Chadwick et al., 2011).

Increasing efforts are required to improve N use efficiency worldwide (Groenestein et al., 2019; Hutchings et al., 2020) and to halve N waste by 2030 (INMS, 2021). In parallel, concerns relating to nitrate (NO_3^-) leaching and GHG emissions have led to increased interest in the use of nitrification inhibitors applied with manures to inhibit microbial processes and reduce N_2O emissions and NO_3^- leaching. There are several types of nitrification inhibitors available, with the most common including 3,4-dimethyl-1H-pyrazole phosphate (DMPP), 2-chloro-6-(trichloromethyl) pyridine (Nitrapyrin), and dicyandiamide (DCD) (Byrne et al., 2020; Di & Cameron, 2016). Several studies have reported that nitrification inhibitors applied with cattle and pig manure can reduce N_2O emissions by up to 50% (Aita et al., 2015; Alfaro et al., 2018; Cahalan et al., 2015; Herr et al., 2020; Montes et al., 2013; Thorman et al., 2020). Nitrification inhibitors such as DCD and DMPP are biodegradable in the soil, and their longevity reduced under warmer temperatures (Di & Cameron, 2016), which may limit their application in temperate summers and tropical climates.

Excreta deposited during grazing by cattle and sheep are often regarded as "non-managed" manure because it is not as easy to control or "manage" the amount of N deposited or the prevailing climatic or storage conditions compared with manures deposited where management is feasible (e.g., livestock housing and hardstanding areas). However, we consider excreta deposited by grazing livestock as being part of manure management because it is possible to influence the factors affecting nutrient losses from dung and urine to some degree, including gaseous emissions. For example, as for manures, interventions such as nitrification inhibitors have been applied to urine- and dung-affected soils to slow the rate of nitrification and thereby potentially reduce N_2O emissions by up to 50% (e.g., Cameron et al., 2014; Simon et al., 2018; Ward et al., 2018). Additionally, nutritional strategies that reduce urinary N excretion or shift the N excretion pathway from urine to dung have been proposed as options to reduce N_2O emissions from livestock excreta (Zhou et al., 2019). These strategies are significantly lowering rates of N_2O emitted from dung compared with urine for every kilogram of N excreted (van der Weerden et al., 2011).

Signatory parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to regularly submit a national GHG inventory. National inventories are calculated following the Intergovernmental Panel on Climate Change (IPCC) guidelines. This includes Tier 1 default GHG emission factors (EFs) for countries that have not determined Tier 2 country-specific EFs or Tier 3 process-based modeling for various GHG sources. An example of an agricultural EF is the proportion of total N (TN) emitted as N_2O–N from manure applied to land (kg N_2O–N kg^{-1} manure-TN applied to land). In the IPCC guidelines, the NH_3 EFs from animal manure are included in the term $Frac_{GASM}$, which relates to the fraction of N in manure that volatilizes as NH_3 and NO_X, where "NO_X" is the collective term for nitric oxide (NO) and nitrogen dioxide (NO_2) (IPCC, 2019; Sherlock et al., 2008). Ammonia represents 93% of the N loss denoted by "$Frac_{GASM}$," with NO_X representing the balance (IPCC, 2019). For the purposes of this paper, we refer to $Frac_{GASM}$ as the "NH_3 emission factor."

There is a large body of research data on GHG and NH_3 emissions from manure management from across contrasting climates and soil conditions. Many of these studies aimed to develop country-specific EFs and typically have a specific focus on geographical range or agricultural source. Examples include the development of Netherlands-specific NH_3 and N_2O EFs for agriculture (Lagerwerf et al., 2019), United Kingdom–specific NH_3 and N_2O EFs for manure application (Thorman et al., 2020), and New Zealand–specific N_2O EFs for livestock grazing (van der Weerden et al., 2020). However, many countries continue to rely on the IPCC Tier 1 default EFs for GHG reporting due to a lack of country-specific information. Tian et al. (2020) notes that GHG inventories using these default EFs show large uncertainties at local to global scales, especially for agricultural N_2O emissions, due to the poorly captured dependence of EFs on spatial diversity in climate, management, and soil physical and biochemical conditions. Emission factors that are disaggregated by environmental and management-related factors are a prerequisite for more accurate inventory accounting of GHG emissions (Tian et al., 2020). The recent refinement of the 2006 IPCC guidelines (IPCC, 2019) includes EF values that have been disaggregated into "wet" and "dry" climates for some of the key N sources. Increasing the number of disaggregated EF values could allow countries that do not have country-specific EFs to report more accurate national inventories.

Recently, the New Zealand government funded the DATAMAN project in support of the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases. The objective of DATAMAN was to collate GHG and NH_3 emission data from across the world, including both developed and developing countries, to create a manure management database that contains EF values along with biotic and abiotic factors. The DATAMAN database provides an opportunity to improve EFs. Such an improvement would assist data compilers to improve the accuracy of national inventories and to quantify the effectiveness of mitigation strategies. The project has initially focused on field-based NH_3 and N_2O emissions from land-applied manures and excreta deposited by grazing livestock, with data collated into Version 1 of the DATAMAN-field database (Beltran et al., 2021).

The objective of the current study was to analyze the DATAMAN-field database to (a) improve NH_3 and N_2O EFs for different N sources and climates and (b) quantify reduction in emissions associated with the use of low emission manure application methods and nitrification inhibitors.

2 | MATERIALS AND METHODS

2.1 | Database description

The DATAMAN-field database (Version 1.0), referred to as the "database" in this paper, was recently described by Beltran et al. (2021). Briefly, this database contains data extracted from existing databases, including ALFAM2 (Hafner et al., 2018), AEDA (AEDA, 2020), ELFE (Vigan et al., 2019), and the 2019 refinement of the 2006 IPCC guidelines (IPCC, 2019). Data were also extracted from published studies, reports, and national datasets from 25 countries. The combined dataset was divided into temperate and tropical wet and dry climates (Beltran et al., 2021) based on the IPCC climate zones (Figure 3A.5.1 in Chapter 3; IPCC, 2019). The distinction between the wet and dry in the tropics was based on 1,000 mm of precipitation (>1,000 mm equating with a wet/moist climate). The division in the temperate region was based on mean annual precipitation/potential evapotranspiration ratio of 1 (>1 equating with a wet/moist climate) (IPCC, 2019). We used GIS data on the IPCC climate zones to categorize zones for each study. In most cases, this was a simple process (e.g., country, or coordinates obtained from the research publication). However, in several instances where the study location was close to the boundary of two climate zones and coordinates were not available, it was necessary to conduct a visual comparison of the climate zone GIS layer with towns noted in the research publication (Beltran et al., 2021).

All collated data were obtained from field-based trials, with most data sourced from temperate wet climate zones (98% of NH_3 EFs and 83% of N_2O EFs), particularly Europe and Oceania (Beltran et al., 2021). As such, we acknowledge the database is not representative of all the regions that produce GHG emissions from land application of manure. For instance, Asia was responsible for the largest agricultural GHG emissions (43%) during the 2010s, followed by the American continent (26%) (Tubiello, 2019; Uwizeye et al., 2020). Emerging economies such as Brazil, China, and India are identified as having the largest increases in N_2O emissions (Tian et al., 2020). Despite these deficiencies, the database contains 7,717 observations records, of which 5,632 include

TABLE 1 Sources of NH_3 and N_2O to be analyzed in the current study aligned with aggregated and disaggregated emission factor values reported in the 2019 refinement of the 2006 IPCC guidelines (IPCC, 2019)

N gas	Key DATAMAN N sources	IPCC[a]			
		Emission and volatilization factors	N source	Level of disaggregation	Source of information (in IPCC, 2019)
NH_3	cattle and swine manure	$Frac_{GASM}$	organic N fertilizers, dung, and urine	no disaggregation	Table 8 A.1
N_2O	cattle and swine manure	EF_1	organic N inputs (crop residues and manure)	wet and dry climates	Table 2 A.2
	cattle urine	EF_{3PRP}	cattle urine	wet and dry climates	Table 4 A.1
	cattle dung		cattle dung	wet and dry climates	Table 4 A.1
	sheep urine		sheep urine	wet and dry climates	Table 4 A.1
	sheep dung		sheep dung	wet and dry climates	Table 4 A.1

[a]EF_1, N_2O losses from organic and synthetic N inputs; EF_{3PRP}, N_2O losses from urine and dung deposited by livestock during grazing of pasture, rangelands, and paddock; $Frac_{GASM}$, N losses of NH_3 and NO_X, with an N loss ratio of 93:7 NH_3/NO_X (IPCC, 2019).

field-based EF values. These were relatively evenly split between N_2O and NH_3, representing, respectively, 56 and 44% of the EF values. The remaining ∼2,000 observations relate to experimental "control" treatments, often used for calculating EF values. Although the database contained information on both manure TN and total ammoniacal N (TAN) content, all EF values were calculated as the fraction of N lost as either NH_3 or N_2O relative to the TN applied or deposited to land, corrected for emissions from non-N control treatments (e.g., de Klein et al., 2020). This definition is in accordance with the IPCC methodology for calculating EF values (IPCC, 2006, 2019).

Our study focused on determining disaggregated EF values for NH_3 and N_2O sources, for which we had large numbers of observations (Table 1). This offers an opportunity to revise and develop EF values that have been disaggregated by wet/dry climates and N source, potentially suitable for IPCC national inventory reporting. We used treatment means and replicate-level data, sourced from the database for most analyses. For generating new EF categories, we determined statistically significant differences in EF values based on animal species and manure type. We retained the wet/dry climate groupings adopted in the 2019 refinement of the 2006 IPCC guidelines (IPCC, 2019).

2.2 | Statistical methods

Due to the skewed nature of the NH_3 and N_2O EF data and the presence of negative values (Beltran et al. 2021), a cube root transformation was applied prior to statistical analysis (Albanito et al., 2017). We fitted all treatment means and replicate data as :replicates"; hence, all means were treated as a single replicate. Although this will weight the experiments with replicates higher when compared to treatment means, on inspection the number of means in most analyses was small and none would be influential. Once significant differences between EF categories were identified from the statistical analysis of transformed data, we used the untransformed raw data to calculate EF means for each category (de Klein et al., 2020). This approach avoids the need to approximate a bias correction that is required when back-transforming transformed data to the measured scale. We then used a bootstrap approach to calculate 95% confidence intervals (Efron & Tibshirani, 1993), where 10,000 bootstrap replicates were applied. All statistical analyses, including pairwise comparisons, have been carried out on the cube root transformed data. Statistically significant results are reported when $p <$ .05. Pairwise comparisons of means have been made using Tukey adjustments to the p values (Tukey, 1949).

All analysis has been carried out in the statistical language R version 3.6.0 (R Core Team, 2019). Linear random effects models have been fitted to the data, where experimental ID was fitted as a random variable, using the Lme4 package (Bates et al., 2015). Tukey pairwise comparisons were carried out using the predictmeans package (Luo et al., 2020).

2.3 | Assessment of data suitability

Before determining EF values for climate zones and N source categories, data within the DATAMAN database (Beltran et al., 2021) were screened for their suitability for inclusion. We assessed a range of experimental conditions that could have biased the experimental results to ensure we excluded any unsuitable data from the statistical analysis. The experimental conditions we examined included measurement techniques, length of experiment, topography, and use of synthetic urine (see Supplemental Material for additional information).

Measurement techniques used for determining NH_3 emissions can be grouped into static and dynamic techniques. Static techniques exclude any air flow across the soil or manure surface, where NH_3 is captured using passive methods, such as acid-treated filter paper, with no air flow across the emitting surface. In contrast, dynamic techniques allow for the effect of air flow over the emitting surface; these methods include dynamic enclosures, wind tunnels, and micrometeorological methods (e.g., integrated horizontal flux). Our analysis showed mean NH_3 EF values were significantly lower from static techniques (Supplemental File S1). These data were excluded because of concern of a possible interaction between the measurement methods; insufficient data prevented an analysis of possible interactions. Nitrous oxide emissions were predominantly measured using the well-established static chamber technique (Clough et al., 2020). This method represents 99.7% of the N_2O EF data in the DATAMAN database, with the remaining 0.3% of EF data (i.e., nine values) generated using dynamic chamber methods such as wind tunnels. Such a small number of values derived from these techniques made it difficult to determine if mean EF values based on static and dynamic techniques differed significantly. However, N_2O fluxes are typically very low, making it difficult to quantify them without a concentration increase in the headspace of static chambers. Therefore, we omitted the nine values based on dynamic chamber methods.

The database includes observations made from N application field trials where the length of experiments was at least 1 d for NH_3 EF values and 14 d for N_2O EF values, as per the criteria established for the development of the database (Beltran et al., 2021). To determine whether the length of experimentation influenced NH_3 EF, data were evaluated using pairwise comparison according to experimental duration for both cattle and swine slurry with data divided into six experiment durations: 1–3, 3–7, 7–14, and >14 d. Our analysis showed length of experiment had a minimal influence on cattle NH_3 EF values and no significant influence on swine EF values (Supplemental File S2). As a precautionary step, we calculated mean EF values for surface-applied cattle and swine slurry where data from experiments with a duration of 1–3 d were either included or excluded. Our results showed that mean EF values remained virtually unchanged (data not shown). Thus, all data were retained for the determination of mean NH_3 EF values.

For N_2O, recent data analysis studies have used a minimum experimental duration of 30 continuous days after N application as a threshold for accepting data (IPCC, 2019; López-Aizpún et al., 2020). The criterion used for accepting N_2O data into DATAMAN was shorter (14 d duration) but excluded studies where there was evidence of N_2O emissions and soil mineral N concentration from the N treatment not returning to background levels (Beltran et al., 2021). In the current study, we analyzed the effect of experiment duration for each manure category, with data divided into six experiment durations: <30, 30–60, 60–120, 120–240, 240–360, and >360 d. We found that length of experiment had a minor influence on EF for cattle and swine manures, with no consistent pattern of increasing EF value with increasing duration (Supplemental File S3). For cattle and sheep urine, we identified five observations where trials were conducted for fewer than 30 d and N_2O fluxes and/or soil NO_3^- concentrations had not returned to background levels; these were removed from the dataset because the associated EF values were considered unreliable. After their removal, shorter experimental durations did not influence N_2O EF values (Supplemental File S4); therefore, all remaining urine data were retained. For cattle dung, EF values were significantly lower when determined from experiments with a duration of <30 d compared with measurements taken over 30–60 d (Supplementary File S5). Because dung can slowly mineralize and release N_2O over longer time periods compared with urine (Krol et al., 2016), we excluded cattle dung EF observations measured for <30 d. Sheep dung data were extremely limited, with only two observations for studies <30 d duration. The results of the cattle dung, based on a larger dataset, compelled us to treat sheep dung similarly to cattle dung, resulting in two observations being omitted due to insufficient evidence for their retention.

The DATAMAN database includes cattle and sheep urine studies conducted on sloping land. Recent research has shown that N_2O EF values are lower on medium- and steep-sloping pastoral land compared with low-sloping land (van der Weerden et al., 2020). It was suggested these topography effects were due to differences in the underlying soil characteristics (e.g., soil water content, soil organic C content) influencing microbial processes. Including these lower EF values from medium- and steep-sloping land would bias the calculation of a mean EF for cattle and sheep urine, thus requiring a weighting of the EF using slope data. Given the limited available data for sloping land relative to the wider dataset and that most excreta N are deposited onto low slopes (Saggar et al., 2015), we excluded urine data obtained from medium and steep slopes. Cattle and sheep dung data were not influenced by slope (Supplemental File S6) and were therefore retained.

We tested whether synthetic and real urine produced different EF values by limiting data to studies where both sources of cattle urine were included as treatments (AEDA, 2020; de Klein et al., 2003; Krol et al., 2016). Previous data analyses have either included (IPCC, 2019; van der Weerden et al., 2020) or excluded (López-Aizpún et al., 2020) synthetic urine studies. Our analysis showed there was no effect of urine type on N_2O EF values (Supplemental File S7). Therefore, both synthetic and real urine EF values were retained and labeled as “urine.”

After excluding data as discussed in the previous sections, the NH_3 and N_2O database used for the statistical analysis included 2,174 and 2,850 EF observations, respectively. For the NH_3 database, the number of data points were split 69 and 31% between cattle and swine, respectively, with all data sourced from temperate wet climates. For the N_2O database,

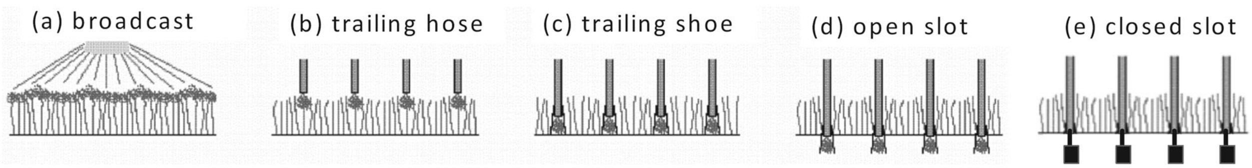

FIGURE 1 Diagrammatic representation showing slurry placements (a) on top of herbage and over entire spreading width with splash-plate broadcast; (b) in bands on top of herbage with trailing hose; (c) in lines below herbage, but above the soil surface, with the trailing shoe; (d) below the soil surface (~5 cm) with open slot/shallow injection; and (e) below the soil surface (~10–15 cm) with closed slot/deep injection (adapted from Lalor, 2014).

the split in data points for N source was 85, 11, and 3% for cattle, sheep, and swine, respectively, and for climate zone 8was 4, 4, 6, and 5% for temperate wet, temperate dry, tropical wet, and tropical dry, respectively.

2.4 | Manure N groupings for EFs

For statistical analyses, the remaining data were further grouped based on species, manure type, and application method in order to provide disaggregated EF values for various livestock manure sources of NH_3 and N_2O. The application method categories included broadcast (manure surface applied with no incorporation), trailing hose, trailing shoe, open slot (which includes shallow injection), and closed slot (which includes deep injection) (Figure 1). Deposition of urine and dung to pasture and rangeland was considered to fall under the "broadcast" classification because there is no mechanical incorporation into the soil.

The project team assessed the level of confidence in the improved EF values based on a combination of number of observations (minimum of 40); number of experiments (minimum of 10); and acceptable coverage of other key variables, including countries (minimum of two countries). In the tables we have indicated improved EF values potentially suitable for national inventory reporting in the tabulated results; those associated with less well represented N sources have italicized EF values. The latter EF values are included in the results for the purposes of comparison with other EFs, scientific interest, and discussion rather than presenting the results as suitable data for inventory compilation. For each reported EF, we also include the 95% confidence interval, defined as the error in the mean EF based on the dataset used for generating the mean value.

2.4.1 | Manure N groupings for NH_3 EFs

The NH_3 EF dataset was analyzed to determine whether cattle and swine should be grouped or separated. Due to a lack of data in certain subclasses, we were unable to separate "cattle" into beef cattle and dairy cattle; therefore, we grouped beef cattle, dairy cattle, and cattle (where beef cattle and dairy cattle were not specified) into a single grouping called "cattle." Restricting data to the largest manure type (i.e., slurry) and most common method of application to land (i.e., broadcast), we observed that the mean NH_3 EF for swine slurry was significantly greater than for cattle slurry (Supplemental File S8). We therefore separated manures by livestock type.

To determine manure type groupings for cattle and swine, we included data where no manure treatments were imposed (e.g., covering, anaerobic digestion, separation), and manure was surface broadcast to land with no incorporation below the soil surface, thus removing data associated with practices known to mitigate NH_3 losses (Thorman et al., 2020). Under these data restrictions, the mean cattle slurry EF was greater than solid manure (Supplemental File S9). For swine manure data, slurry was the main type (n = 300), with solid manure representing six EF values. We therefore focused on swine slurry for determining EF values.

To assess slurry application technique on EFs, we evaluated broadcast application and alternative low trajectory or injection methods, including trailing hose, trailing shoe, and open slot, for both cattle and swine slurry application. Swine slurry also included "closed slot" application. An assessment of the influence of manure N application rate on EFs for each manure group and application method showed there was no effect.

There were insufficient data to explore the grouping of NH_3 EF values for animal urine and dung deposited during grazing.

2.4.2 | Manure N groupings for N_2O EFs

For N_2O, an analysis of cattle manure data showed no significant difference between manure types (dirty water, slurry, solid manure) (Supplemental File S10). Dirty water describes the water derived from washing down floors of dairy milking parlors and is sometimes referred to as dairy shed effluent or brown water (Beltran et al., 2021; Pain & Menzi, 2011). The lack of significant difference in manure types was unexpected because slurry typically contains higher levels of readily available C and mineral N compared with solid manure. Our analysis showed a higher mean N_2O EF for slurry; however, this was not significantly greater than for solid manure and dirty water, probably due to the limited size of the dataset. We grouped all cattle manure types into a single category called "manure" and determined whether manure N application rate had a significant influence on EFs. Results showed there was no application rate effect ($P > .05$). Emission factors for cattle manure were then separated on the basis of "wet" and "dry" climates to align with the disaggregated EF based on climate in the 2019 refinement (IPCC, 2019). Similar to cattle manure, there was no significant swine manure type effect (dirty water, slurry, and solid manure) on N_2O EF (Supplemental File S11). We also found there was no swine manure N application rate effect on EF. All swine data were produced in "wet" climates; therefore, we determined a swine manure EF value for this climate zone.

We observed significantly greater cattle urine EF values compared with sheep urine, whereas cattle dung EF values were significantly greater than sheep dung (Supplemental File S12). Therefore, both cattle and sheep urine and dung were each separated into wet and dry climate categories for consistency.

Dietary N content has a significant effect on partitioning of excreta N into urine and dung N (Valk, 1994). The 2019 refinement of the 2006 IPCC guidelines assumed a urine/dung N ratio of 0.66:0.34 for the reported "excreta" EF values (IPCC, 2019). Although this ratio may be considered suitable for grazing systems with a relatively high feed quality, it is not representative of low-quality N animal diets in regions such as sub-Saharan Africa, where urine/dung N ratios can be as low as 0.31:0.69 (Zhu et al., 2020). Our study provides an opportunity to determine "excreta" EF values for cattle and sheep in wet and dry climates for different dietary N contents. To account for the effect of dietary N on urine/dung N ratio, we used a relationship developed by Pacheco et al. (2018) using a feed quality database where dietary N content ranged from 0.8 to 5.0% dry matter (DM), including information from beef cattle, dairy cattle, deer, and sheep. Excreta EF values were calculated for two contrasting urine/dung N ratios (0.66:0.34 and 0.35:0.65), assuming a high and low dietary N content of 3.3 and 0.8%, respectively. A value of 3.3% is representative of temperate grass/clover systems (e.g., average of New Zealand dairy and sheep and beef pastures; Giltrap & McNeill, 2020), and a value of 0.8% is representative of forages and feeds in drier climates (e.g., Ali et al., 2019).

The DATAMAN database includes studies assessing the effectiveness of nitrification inhibitors to reduce N_2O emissions and associated EF values from manure, urine, and dung. However, the dataset was unbalanced, with the number of observations where no nitrification inhibitor was applied being five times greater than the number of observations that included a nitrification inhibitor. We therefore limited the dataset to studies where nitrification inhibitors were used. This resulted in pairwise comparisons for different N sources, where the number of observations varied from relatively small numbers (e.g., 32 observations of N_2O EF for swine slurry with or without inhibitors, split 50:50) to relatively large numbers (e.g., ∼500 observations of N_2O EF for cattle urine with or without inhibitors, split roughly 50:50). For our analysis of sheep urine data, we excluded two EF outliers where 3,4-dimethylpyrazole phosphate had been applied 2 or 4 wk prior to urine deposition. These two values had very large standard errors, with mean EF values >8% of applied TN.

3 | RESULTS

3.1 | Ammonia EFs

Field experiments on NH_3 emissions from manures were limited to temperate wet climates. All of the NH_3 findings reported here are therefore directly applicable to these climates, but caution is needed if considering their application to temperate dry and tropical climates, given the influence of temperature and soil moisture conditions on NH_3 emissions from manures (e.g., Hafner et al., 2019; Thorman et al., 2020).

The NH_3 EF values for cattle solid manure and slurry surface broadcast onto land were, respectively, 0.03 and 0.24 kg NH_3–N kg^{-1} TN applied (Table 2). All low-trajectory and injection application techniques reduced NH_3 emissions from cattle slurry. The open slot application had the greatest effect, reducing NH_3 EFs by 62% compared with broadcast application of slurry. Low-trajectory methods such as trailing hose and trailing shoe reduced NH_3 EFs by, respectively, 35 and 46% relative to broadcast application. Based on our quantitative "level of confidence" criteria (see Section 2.4), all cattle solid manure and slurry NH_3 EF values are regarded as potentially suitable for inventory calculations.

Swine slurry that had been surface broadcasted onto land had an NH_3 EF of 0.29 kg NH_3–N kg^{-1} TN (Table 3). Trailing hose, closed slot, and open slot application produced the largest reduction in NH_3 EF at, respectively, 52, 58, and 46% compared with broadcast application. With a reduction of only 2% compared with broadcast, the trailing shoe was the least effective when comparing the raw means, but it is important to note that the statistical comparison of application techniques was conducted on transformed EF data, where random effects were included in the analysis. This provided a more robust analysis of the data. However, the skewed nature of some data has resulted in raw means being similar for some application techniques (e.g., broadcast and trailing shoe). This is partly influenced by the limited number of observations; therefore, these raw means should be interpreted with caution.

TABLE 2 Effect of cattle manure type (solid vs. slurry) and slurry application method on NH_3 emission factors (EFs) based on total N (TN) load applied to land in temperate and wet climates

Treatment	Tukey's pairwise comparison[a]	*n*	Raw mean NH_3 EF	Reduction in EF_3 due to application method compared with broadcast
			kg NH_3–N kg^{-1} TN	%
Manure types (broadcast only, no soil incorporation)				
Solid	A	43	0.030 (0.025–0.035)	
Slurry	B	465	0.242 (0.229–0.256)	
Slurry application methods				
Broadcast	A	465	0. 242 (0.229–0.256)	NA[b]
Trailing hose	B	248	0.159 (0.139–0.190)	35
Trailing shoe	C	207	0.129 (0.115–0.145)	46
Open slot	D	178	0.092 (0.081–0.105)	62

Note. Statistical analyses were performed on transformed data with untransformed means shown in the table. Values in parentheses are 95% confidence intervals. The % reduction in NH_3 EF is relative to broadcast slurry application.

[a]At the 5% level.

[b]Not applicable.

TABLE 3 Effect of application method on swine slurry NH_3 emission factors (EFs) based on total N (TN) load applied to land in temperate and wet climates

Treatment	Tukey's pairwise comparison[a]	*n*	Raw mean of NH_3 EF	Reduction in NH_3 EF due to application method compared with broadcast
			kg NH_3–N kg^{-1} TN	%
Broadcast	A	300	0.289 (0.264–0.322)	NA[b]
Trailing hose	B	165	0.138 (0.125–0.159)	52
Sources and values below are not sufficiently robust for inventory calculations				
Open slot	B	*38*	*0.156 (0.105–0.231)*	*46*
Trailing shoe	BC	*21*	*0.284 (0.212–0.360)*	*2*
Closed slot	C	*18*	*0.103 (0.032–0.360)*	*64*

Note. Groupings are based on transformed data but ordered according to raw means. Raw means are not necessarily in rank order due to large imbalances in sample sizes and the random effect of the experiment ID. Values in parentheses are 95% confidence intervals. Based on our quantitative "level of confidence" criteria (Section 2.4), italicized EF values are regarded as not sufficiently robust for inventory calculations.

[a]At the 5% level.

[b]Not applicable.

3.2 | N_2O EFs

3.2.1 | Land-applied manure

Based on our statistical analysis, we identified three separate livestock vs. land-applied manure type combinations for determining disaggregated Tier 1 EF values (two cattle and one swine manure category; Table 4). The cattle manure categories were separated according to wet and dry climates; the swine manure was restricted to wet climates only.

Land-applied cattle manure in wet climates had a mean EF value of 0.0050 kg N_2O–N kg^{-1} N applied, whereas a lower value of 0.0031 kg N_2O–N kg^{-1} N applied was calculated for dry climates. Land-applied swine manure in wet climates had an EF value of 0.0110 kg N_2O–N kg^{-1} N applied, which is more than double that of cattle manure under the same climate classification (Table 4). Based on our quantitative "level of confidence" criteria (see Section 2.4), all cattle and swine manure N_2O EF values are regarded as potentially suitable for inventory calculations.

Low-trajectory and injection methods for cattle and swine slurry application generally did not influence N_2O EF values, apart from trailing hose, which significantly reduced the EF for swine slurry (Supplemental File S13). However, the num-

TABLE 4 Comparison of improved emission factor (EF) values for soil-based N_2O emissions from manures applied to land based on current analysis, with IPCC 2019 disaggregated EF and IPCC 2006 Tier 1 EF values (IPCC, 2019, 2006)

N source and climate zone[a]	Current analysis		IPCC 2019 disaggregated Tier 1 EF		IPCC 2006 Tier 1 EF	
	Mean (*n*)	Uncertainty range[b]	Mean	Uncertainty range[b]	Mean	Uncertainty range[c]
	kg N kg^{-1} N applied					
Cattle manure, dry climates	0.0031 (115)	0.0017–0.0069	0.005	–0.003–0.013	0.010[d]	0.003–0.03
Cattle manure, wet climates	0.0050 (428)	0.0041–0.0061	0.006	0.001–0.011		
Swine manure, wet climates	0.0110 (60)	0.0082–0.0145				

[a]Wet climates are considered as temperate and boreal zones where the ratio of annual precipitation/potential evapotranspiration is >1, and tropical zones are where annual precipitation >1,000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation/potential evapotranspiration <1, and tropical zones where annual precipitation <1,000 mm.
[b]Values are 2.5th to 97.5th percentile.
[c]Method for assessing 2006 IPCC uncertainty range is unreported.
[d]Includes synthetic N fertilizer because the 2006 IPCC uncertainty range did not split synthetic fertilizer and organic N application.

TABLE 5 Comparison of refined emission factor (EF) values for N_2O emissions from cattle and sheep urine and dung deposited on to land in wet and dry climates from current analysis, with IPCC 2019 disaggregated EF values (Table 4A.1, page 11.34; IPCC 2019)

N source and climate[a]	Current analysis		IPCC 2019 disaggregated EF	
	Mean	Uncertainty range[b]	Mean	Uncertainty range[b]
	kg N kg^{-1} N deposited			
Cattle urine, wet climates	0.0095 (923)[c]	0.0088–0.0103	0.0077	0.0003–0.0382
Cattle dung, wet climates	0.0020 (461)	0.0017–0.0027	0.0013	0.0000–0.0053
Cattle urine, dry climates	0.0027 (64)	0.0019–0.0039	0.0032	0.0003–0.0093
Cattle dung, dry climates	0.0007 (79)	0.0005–0.0009	0.0007	0.0001–0.0012
Sheep urine, wet climates	0.0043 (145)	0.0033–0.0058	0.0039	0.0004–0.0180
Sheep dung, wet climates	0.0005 (143)	0.0002–0.0008	0.0004	−0.0019–0.0027
Sources and values below are not sufficiently robust for inventory calculations				
Sheep urine, dry climates	*0.0027 (2)*	*CBD*[d]	0.0031	0.0004–0.0091
Sheep dung, dry climates	*0.0105 (1)*	*CBD*	0.0021	−0.0001–0.0091

Note. Based on our quantitative "level of confidence" criteria (Section 2.4), italicized EF values are regarded as not sufficiently robust for inventory calculations.
[a]Wet climates are considered as temperate and boreal zones where the ratio of annual precipitation/potential evapotranspiration >1 mm, and tropical zones are where annual precipitation >1,000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation/potential evapotranspiration <1 m, and tropical zones where annual precipitation <1,000 mm.
[b]Values are 2.5th to 97.5th percentile range, reflecting the 95% confidence interval for the mean.
[c]Values in parentheses are the number of data.
[d]Cannot be determined.

ber of observations available for the swine slurry analysis was limited to 50, with only nine observations relating to trailing hose. Caution is therefore advised when interpreting these results.

3.2.2 | Urine and dung from grazing animals

For excreta deposited during grazing, we identified six separate livestock vs. manure type combinations for determining disaggregated Tier 1 EF values (two cattle and one sheep category for both urine and dung; Table 5). Based on our quantitative "level of confidence" criteria (see Section 2.4), we had sufficient justification to separate the cattle urine and dung categories into wet and dry climates, but for sheep urine and dung we only had sufficient data for wet climates. Sheep urine and dung data for dry climates were limited to, respectively, one and two observations, with all data sourced from a single country (China). Although we estimate EF values for sheep urine and dung in dry climates (Table 5, shown in italics), these values are not considered sufficiently robust to represent disaggregated Tier

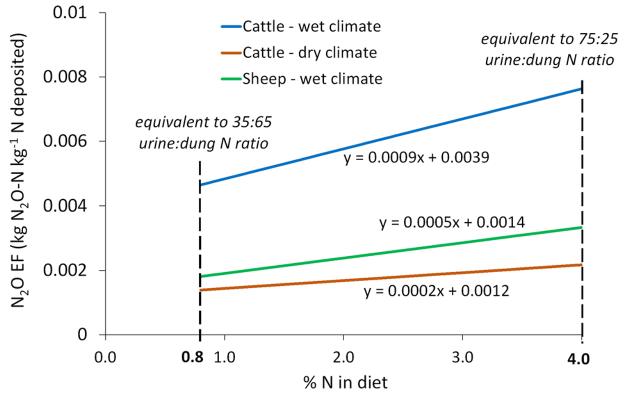

FIGURE 2 Influence of dietary N content on cattle and sheep excreta N_2O emission factor (EF) for wet and dry climates, where effect of dietary N on urine and dung N partitioning was modeled (Pacheco et al., 2018).

1 EF values. We have only included them for comparative purposes.

Cattle and sheep urine and dung N_2O disaggregated Tier 1 EF categories are aligned with the EF categories presented in the 2019 refinement of the 2006 IPCC guidelines (IPCC, 2019; Appendix 11A.4), with each N source category disaggregated by wet and dry climates (Table 5). However, the IPCC guidelines recognize that the number of data points for sheep excreta in dry climates is very limited, and Table 11.1 of the updated guidelines does not disaggregate between wet and dry climates for sheep excreta.

The N_2O EF values for cattle urine and dung in wet climates were, respectively, 0.0095 and 0.0020 kg N_2O–N kg^{-1} N deposited (Table 5). These were approximately three times greater than the EF values for urine and dung in dry climates (0.0027 and 0.0004 kg N_2O–N kg^{-1} N, respectively). Sheep N_2O EF values were consistently lower than the cattle values. In wet climates, the sheep urine N_2O EF was approximately half the value for cattle urine, and the sheep dung N_2O EF was one-quarter of that for cattle dung.

To calculate overall "excreta" EF values, we used the cattle and sheep urine and dung values (Table 5) and two contrasting urine/dung N ratios (0.66:0.34 and 0.35:0.65) (Table 6). We calculated Tier 1 excreta EF values for cattle in both wet and dry climates, although an EF value for sheep excreta is limited to wet climates due to insufficient robust data for calculating Tier 1 values for dry climates. The influence of dietary N content on these EF values is illustrated in Figure 2, where diet N content ranges from 0.8 to 4% of DM.

Nitrification inhibitors significantly reduced the EF values for swine slurry, cattle urine, cattle dung, and sheep urine. Reductions ranged from 56% (cattle urine) to 84% (cattle dung), where the majority of studies used DCD as the active ingredient, and the mean application rate was between 9 and 20 kg DCD ha^{-1} (Table 7). However, results for swine slurry

TABLE 6 Comparison of revised emission factors (EFs) for N_2O emissions from excreta deposited on to land in wet and dry climates based on current analysis

N source and climate[a]	Current analysis: Based on urine/dung N ratio of 0.66:0.34		Current analysis: Based on urine/dung N ratio of 0.35:0.65		2019 IPCC EF, based on urine/dung N ratio of 0.66:0.34		2006 IPCC EF	
	Mean	Uncertainty range[b]	Mean	Uncertainty range[b]	Mean	Uncertainty range[b]	Mean	Uncertainty range[c]
	kg N kg^{-1} N deposited							
Cattle excreta, wet climates	0.0070	0.0062–0.0081	0.0046	0.0040–0.0058	0.006	0.000–0.026	0.02	0.007–0.06
Cattle excreta, dry climates	0.0020	0.0015–0.0028	0.0014	0.0010–0.0019	0.002	0.000–0.006		
Sheep excreta, wet climates	0.0030	0.0020–0.0045	0.0018	0.0010–0.0030	0.003	0.000–0.010	0.01	0.003–0.030

Note. Excreta EF calculated from urine and dung values but weighted based on an estimated split in N between urine and dung using two different urine/dung N ratios of 0.35:0.65 and 0.66:0.34, respectively (Pacheco et al. 2018). Values are compared with those reported in 2019 and 2006 IPCC guidelines.

[a]Wet climates are considered as temperate and boreal zones where the ratio of annual precipitation/potential evapotranspiration is >1, and tropical zones are where annual precipitation is >1,000 mm. Dry climates occur in temperate and boreal zones where the ratio of annual precipitation/potential evapotranspiration, <1 and tropical zones are where annual precipitation is <1,000 mm.

[b]Values are 95% confidence interval, based on 2.5th to 97.5th percentile and converted to a proportion of the mean (see Fig. 3.3b in Volume 1, Chapter 3 "Uncertainties" in IPCC [2006]).

[c]Method for determining 2006 IPCC uncertainty range is unreported.

TABLE 7 Comparison of emission factor (EF) values (applied/deposited) for N sources untreated (control) or treated with a nitrification inhibitor, type of nitrification inhibitor used, and average rate of dicyandiamide (DCD) applied

N source	Control (mean, number of observations)	With nitrification inhibitor (mean, number of observations)	Type of nitrification inhibitor (*n*)	Average rate of DCD applied	*P* value	Reduction in EF
	kg N kg^{-1}			kg ha^{-1}		%
Cattle manure (slurry and dirty water)	0.0048 (93)	0.0038 (94)	DCD (93); nitrapyrin (1)	10	NS	
Cattle urine	0.0112 (238)	0.0061 (264)	DCD (245); Piadin (15); nitrapyrin (n)	15	<.05	45
Cattle dung	0.0012 (39)	0.0004 (43)	DCD 100%	15	0.05	63
Sources and values below are not sufficiently robust for inventory calculations						
Swine slurry	*0.0217 (16)*	*0.0096 (16)*	*DCD 100%*	*9*	*<.05*	*56*
Sheep urine	*0.0016 (27)*	*0.0006 (25)*	*DCD (24); DMPP (1)*	*20*	*<.05*	*62*

Note. All cattle and sheep dung and urine were deposited onto pasture. The dataset was limited to studies where nitrification inhibitors were assessed. Based on our quantitative "level of confidence" criteria (Section 2.4), italicized EF values are regarded as not sufficiently robust for inventory calculations.

and sheep urine should be interpreted with caution due to the restricted number of observations and relatively small number of representative countries (swine slurry all from Brazil; sheep urine from New Zealand and the United Kingdom). Cattle dirty water was surface applied, cattle slurry was either broadcast or applied by trailing shoe, and swine slurry was either broadcast or shallow injected. Nitrification inhibitor application did not significantly reduce the N_2O EFs for cattle manures, which was a combination of slurry and dirty water manure types. A further analysis of these manure types showed no difference in their response to nitrification inhibitors. Our dataset did not contain any studies where nitrification inhibitors were applied to sheep dung.

4 | DISCUSSION

The DATAMAN-field database has provided an opportunity to improve NH_3 and N_2O EFs, which may assist inventory compilers with improving the accuracy of national inventories and quantify the effectiveness of mitigation strategies. A statistical analysis of 2,174 NH_3 and 2,850 N_2O EF observations has led to the development of EFs disaggregated by climate and N source. Furthermore, we have quantified the reduction in emissions associated with the use of low-emission manure application methods and nitrification inhibitors.

However, we acknowledge that the database is unbalanced, with greater representation of temperate wet climates. As such, we have only recommended disaggregated Tier 1 EF values for N sources that are sufficiently represented. The level of confidence we have in the EF values is based on a combination of number of observations, confidence intervals, and coverage of key regions (see Section 2.4). For N sources that are less well represented, we included italicized EF values (e.g., Table 2) for the purposes of comparison, scientific interest, and discussion rather than presenting the results as recommended values for inventory compilation.

4.1 | Ammonia EFs

4.1.1 | Cattle and swine manure

We have developed new disaggregated Tier 1 NH_3 EF values based on livestock type and manure type. Our analysis showed that cattle solid manure (e.g., farmyard manure) broadcast on to soils in temperate wet climates has an NH_3 EF value of 0.030 kg NH_3–N kg^{-1} N applied, which is significantly lower than 0.242 kg NH_3–N kg^{-1} N applied as determined for cattle slurry under the same climatic conditions (Table 2). Cattle solid manures typically have lower TAN contents compared with slurry, resulting in lower NH_3 EF values (Sommer & Hutchings, 2001; Sommer et al., 2019). Indeed, the mean TAN contents of cattle solid manure and slurry in the current study were, respectively, 0.68 and 1.34 kg TAN t^{-1} manure fresh weight. The lower TAN content of solid manure is possibly due to these manure types being mixed with bedding and because, depending on the method of collection, solid manure may have less urinary N associated with it compared with slurry. Solid manures are also generally stored for longer periods, which increases the likelihood of reduced TAN through NH_3 emissions prior to land application and, if conditions are favorable, during composting of stored manure (Sommer & Hutchings, 2001). Our EF value for solid manure in temperate wet climates is one-eighth of the IPCC Tier 1 $Frac_{GASM}$ default value of 0.20 kg NH_3–N kg^{-1} N applied for "organic N fertilisers" (i.e., manures) (IPCC, 2006). This EF value remained relatively unchanged with the 2019 refinement of the guidelines, increasing slightly to 0.21; however, this is the sum of both NH_3 and NO_X emissions (IPCC, 2019). The NH_3 component of $Frac_{GASM}$ was 0.197 kg NH_3–N kg^{-1} N applied (Table 8A.1; IPCC, 2019), which is still substantially greater than our reported value for cattle solid manure. In contrast to solid manure, our values for cattle slurry (0.242) were a little higher than that of the IPCC's default value for organic N fertilizer applied to land. It is important to note that the N sources for the IPCC Tier 1 default values include all manures and dung and urine.

Swine slurry that has been surface broadcast to soils in temperate wet climates has an NH_3 EF value of 0.289 kg NH_3–N kg^{-1} N applied, which was significantly higher than that of cattle slurry (0.242 kg NH_3–N kg^{-1} N applied). This difference may relate to the TAN content of the slurry, which averaged 3.27 and 1.34 kg TAN t^{-1} manure fresh weight for swine and cattle, respectively. As for cattle slurry, the swine slurry EF value is greater than the IPCC default value for organic N fertilizer applied to land (0.21 kg NH_3–N kg^{-1} N applied). The inclusion of more recent studies has presented an opportunity to improve Tier 1 EF values through disaggregation of the current "organic N fertilizer" category used in the IPCC guidelines. Another consideration when comparing published EF values is the source data used for these calculations. In the current study, we excluded data where manures were injected or incorporated into soil because these are well-established mitigation practices (Hou et al., 2015; Smith et al., 2000; Sommer et al., 1997) that would influence the magnitude of the mean EF for a given N source. By separating out the effect of application methods, we have been able to quantify the mitigatory effect of low-trajectory (trailing shoe, trailing hose) and injection application techniques on NH_3 emissions from cattle and swine slurry; this is explored further in Section 4.1.2.

Although the IPCC requires EF values on the basis of TN applied (IPCC, 2006, 2019), countries that are members of the United Nations Economic Commission for Europe are required to submit NH_3 emission inventories where EF values are based on TAN applied (European Environment Agency, 2019). From a process viewpoint, NH_3 emissions based on TAN applied to land may be more appropriate because NH_3 losses occur primarily from the surface of ammoniacal solutions in water, such as slurries and solid manure (Sommer et al., 2019). We calculated cattle and swine slurry EF values based on TAN application to compare with those based on TN application. As noted above, we observed a significant difference in EFs for cattle and swine slurry when based on TN. However, there was no significant difference in EFs when based on TAN applied, with cattle and swine having EF values of, respectively, 0.49 and 0.44 kg NH_3–N kg^{-1} TAN applied. This supports the findings of Chadwick et al. (2011), who suggested it is the readily available N and not the TN applied that drives the NH_3 value. We include NH_3 EF values based on TN in the current paper because we want to provide countries with more accurate, disaggregated NH_3 EFs that can be directly implemented by inventory compilers for UNFCCC national inventory reporting.

4.1.2 | Slurry application technique

Our study showed emission reductions of 35% for trailing hose, 46% for trailing shoe, and 62% for open slot injection of cattle slurry in temperate wet climates. The reductions in NH_3 emissions due to these methods are generally lower in the current study than those reported by Webb et al. (2010) and Hafner et al. (2018). This may reflect differences in the dataset used for the analysis; whereas the DATAMAN database incorporates the ALFAM2 database (Hafner et al., 2018), additional data from more recent studies are also now included. Model results by Hafner et al. (2018) showed that low-trajectory and injection methods reduced NH_3 emissions compared with broadcast application by about 30, 50, and 70% for trailing shoe, trailing hose, and open slot injection, respectively. Their expectation was that emissions from trailing shoe would be lower than trailing hose because the slurry is banded on the soil surface below the foliage. Hafner et al. (2018) suggested the results of their analysis may have been affected by an unbalanced dataset. In contrast, and in agreement with Webb et al. (2010), analysis of our expanded dataset showed trailing shoe to be more effective at reducing NH_3 EFs compared with trailing hose, as expected for this application technique.

For both cattle and swine slurry, the results indicate that the deeper slurry is inserted/injected into soil, the lower the NH_3 emissions. Webb et al. (2010) reported a similar finding based on simple averages of reported reductions in NH_3 emissions relative to broadcast applications. Our analysis has shown that trailing hose, trailing shoe, and open slot injection application techniques produce significantly lower cattle slurry NH_3 emissions and are significantly different from each other. Sommer and Hutchings (2001) suggested the reduction in emission is most likely related to the reduced area of slurry exposed to air. This would reduce the NH_3 emission per unit of time. However, for trailing hose and trailing shoe applications, the higher application rate within the bands of slurry would mean that the time required for infiltration and the duration of the emission would be correspondingly extended. Because slurry applications are typically made during daylight hours, extended emissions into the relatively calm night period, when conditions are less favorable for NH_3 volatilization, is likely to result in lower cumulative emissions from trailing hose and trailing shoe applications compared with broadcast application. All low-trajectory and injection application techniques have been found to reduce NH_3 emissions compared with broadcast application (Hafner et al., 2018; Hou et al., 2015; Smith et al., 2000; Sommer et al., 1997). However, a recent analysis of data from the United Kingdom showed no significant difference in NH_3 emissions from slurry applied using broadcast and trailing hose techniques in the autumn, with soil moisture content suggested as an important factor (Thorman et al., 2020). These authors suggest that when soils are too dry, hydrophobicity can reduce slurry infiltration, thereby increasing the duration of the emission event. Likewise, soils that are too wet may limit slurry infiltration of the band, which also extends the duration of NH_3 emissions. Application technique had a similar effect on the NH_3 EF for swine slurry, although our confidence in the mean EF values and percentage reductions in NH_3 loss for trailing shoe, open slot, and closed slot techniques is not as high compared with broadcast and trailing hose due to the lower number of observations (all having <40 observations). Given the smaller dataset for trailing shoe, open slot, and closed slot techniques, we would not recommend the reduction in NH_3 to be considered as EF values suitable for national inventory reporting. In the future, inclusion of additional data may help to improve our confidence in mean EF values for swine slurry applied by a wider range of techniques.

4.2 | N_2O EFs

4.2.1 | Cattle and swine manure

We have recommended three disaggregated Tier 1 N_2O EF values for livestock manure applied to land. Two of these relate to cattle manure, split into "wet" and "dry" climates, while the third relates to swine manure applied to land in wet climates. There was insufficient data to generate a "swine manure - dry climate" EF value. We did not observe any significant differences in manure types and therefore pooled the data within each livestock class to determine overall N_2O EF values for cattle and swine. As noted earlier, the lack of significant difference in manure types was unexpected, given slurry typically contains higher levels of mineral N compared to solid manure (Chadwick et al., 2011). The lack of significant differences in manure type supports the finding by Rochette et al. (2008) who also found no consistent difference among manure types when comparing N_2O emissions from land-applied liquid and solid manures. These authors highlighted the complex interaction between manure types and soil properties (e.g., texture, structure) influencing the processes responsible for N_2O production and emission.

Climate had a strong effect on N_2O EF values for cattle manure applied to soil, with EFs for wet climates being nearly double those for dry climates. This is most likely a reflection of generally high soil water contents in wet climates. Nitrous oxide emissions and EF values generally increase directly with soil water content, with large increases in emissions when soil water content exceeds 65% water filled pore space (WFPS) (Kasper et al., 2019; McTaggart et al., 2002; Velthof & Oenema, 1995), similar to that reported in our study (mean WFPS of 64% for temperate wet climates). Our N_2O EF value (kg N_2O–N kg^{-1} N applied) for cattle manure in wet climates (0.005) is similar to the IPCC (IPCC, 2019) N_2O EF value for "organic" N inputs (i.e., manures and crop residues: 0.006). In contrast, our N_2O EF value for dry climates (0.003) was lower than the IPCC value for "organic" in dry climates (0.005), which may reflect the expanded dataset used in the current study.

The N_2O EF value for swine manure applied to land in wet climates was 0.011 kg N_2O–N kg^{-1} N, which is double that of cattle manure. This contrasts with the findings of Chadwick et al. (2000), who observed higher N_2O emissions from dairy cattle compared to swine slurry, which they attributed to differences in the C content of the slurries and to the fine solids in the dairy slurry blocking soil pores and enhancing anaerobic soil conditions. Our analysis showed that swine manure had a higher mean manure N content compared to cattle manure (respectively 3.6 vs. 1.6 kg N t fresh weight^{-1} on average; data not presented). Similarly, the swine manure TN application rate was, on average, 24% greater compared with cattle manure (respectively 130 vs. 105 kg N ha^{-1}; data not presented) while manure TAN application rates were on average 27% greater for swine compared with cattle (data not presented). These differences may help to explain our higher swine manure N_2O EF value. Chadwick et al. (2011) suggested that a nonlinear increase in N_2O emissions with increasing manure N application rate could be expected, which may relate to soil oxygen being depleted more rapidly, thereby increasing N_2O production via enhanced denitrification activity. However, our analysis of 543 cattle manure EF values and 51 swine manure EF values showed manure N application rate does not have a significant effect on N_2O EF values, suggesting further investigation is required to assess why the mean EF for swine is greater than that for cattle manure.

Slurry application methods that reduce NH_3 losses can retain more N in the soil, which could stimulate N_2O emissions (Webb et al., 2010). This "pollution swapping" effect has been observed by some (Aita et al., 2014, 2019; Thorman et al., 2020). For example, Aita et al. (2019) reported that shallow injection of slurry increases N_2O emissions by 77% compared with broadcast application while reducing NH_3 emissions (by ~70%). Webb et al. (2010) suggested that slurry needs to be injected deeper in the soil so that any N_2O produced via denitrification at depth will have a greater opportunity to be further reduced to dinitrogen (N_2) as it diffuses to the soil surface. In our analysis, we did not find any significant effect of cattle slurry application techniques on N_2O EF values; however, our analysis was restricted by the number of observations, so these results should be interpreted with caution. Chadwick et al. (2011) noted that N_2O emissions following slurry injection may increase, decrease, or remain unchanged when compared with broadcast application. These authors suggest injecting slurry when soil conditions promote denitrification will increase N_2O emissions relative to broadcast, whereas soil with a higher aeration status may produce similar N_2O emissions following broadcast and injection of slurry.

4.2.2 | Cattle and sheep urine and dung

Our analysis of cattle and sheep urine and dung data showed significant differences according to livestock type and excreta type, providing the basis for generating updated and disaggregated EF values that can be compared with the disaggregated EF values reported in the 2019 IPCC guidelines (Table 4A.1; IPCC, 2019). The major differences in the updated values and those reported by the IPCC (IPCC, 2019) are due to the inclusion of more recent studies.

Given the large difference in N_2O emissions for urine and dung, disaggregation of EFs into dung and urine has been promoted over recent years (e.g., Chadwick et al., 2018; de Klein et al., 2001; Krol et al., 2016; van der Weerden et al., 2011, 2020). This would provide a more accurate assessment of N_2O emissions from animal excreta deposited during grazing. Recently, van der Weerden et al. (2020) outlined the potential mechanisms influencing the difference in dung and urine EFs. The readily available mineral N in urine often exceeds the N requirements of pasture, with the excess being vulnerable to N_2O emissions via nitrification and denitrification. In contrast, dung contains very little mineral N because most of the N in dung is organic N. Although this organic N can become available through decomposition and mineralization, these processes can take several months, depending on rainfall and temperature (Krol et al., 2016), resulting in a supply of mineral N concentrations that is less likely to exceed the N requirements of pasture.

Our criteria of accepting data help to ensure the calculated EF values are based on nonbiased data. One of the criteria used was the length of experiment duration because a pairwise comparison showed that this parameter had a significant effect on EF values. An additional criterion for studies conducted for fewer than 30 d was the need for soil mineral N levels from N treatments to return to background or "control" levels, which could only be determined where information was provided in publications. We excluded studies conducted for <30 d where insufficient data were provided. We accept that these criteria for acceptance of urine and dung EF data are not 100% rigorous, and therefore it is possible that some observations have been included from studies that were terminated too soon, thereby underestimating the EF values. Likewise, it is possible that some omitted observations from studies that were <30 d may have been suitable for inclusion.

Nitrous oxide EF values for cattle dung and urine in wet climates are approximately four times higher than those from dry climates. As noted above, N_2O EF values increase with increasing soil water content. We reported a mean WFPS of 65% for the first 30 d following urine and dung deposition in wet climates, whereas dry climates had a mean value of 34%. We do not consider the sheep urine and dung EF values for dry climates suitable for national inventory reporting, given the very limited number of observations (fewer than three for either dung or urine).

To estimate overall "excreta" EFs, we used the urine and dung EFs values combined with an assessment of the partitioning of N in urine and dung based on dietary N content. An increase in dietary N content will increase the ratio of urine/dung N in excreta (Selbie et al., 2015; Valk, 1994). Our "excreta" EF values for differing dietary N content were based on a relationship between dietary N content ranging from 0.8 to 5% and urine/dung N partitioning (Pacheco et al., 2018). Dietary N content can vary greatly, with tropical grasses typically having an N content of ~1% of DM (e.g., Ali et al., 2019), arid and semi-arid grasslands typically containing 1–2% N (e.g., Keba et al., 2013), and temperate mixed sward grass/legume pastures containing 3–4% N (e.g., Giltrap & McNeill, 2020). Our calculated excreta EF values based on the urine/dung N ratio of 0.66:0.34 (Table 6), the same ratio used for the IPCC refinement's calculation of "excreta" EF, compare well with the IPCC values. However, because the 0.66:0.34 ratio reflects a diet with 3.3% N, this ratio and the resulting EF values are possibly unsuitable for grazing systems using low-N diets (Zhu et al., 2021). We therefore also included excreta EFs based on lower-N diets (Table 6; Figure 2). Recommending cattle and sheep excreta EF values that account for climate and dietary N content provides inventory compilers with the opportunity to estimate N_2O emissions from sheep and cattle grazing diets with different N contents.

4.2.3 | Role of nitrification inhibitors

Nitrification inhibitors are compounds that slow the conversion of NH_4^+ to NO_3^- in the soil, thereby reducing N_2O emissions from agricultural land (Di & Cameron, 2002). Dicyandiamide, the most commonly used nitrification inhibitor in research trials, acts as a bacteriostatic agent by inhibiting the first stage of nitrification: the oxidation of NH_4^+ to nitrite (NO_2^-). In our analysis, DCD represented 95% of the observations, with nitrapyrin, DMPP, and Piadin (1H-1,2,4-triazole and 3-methylpyrazole; SKW Stickstoffwerke Piesteritz) representing the remaining 5%. Our results showed that nitrification inhibitors were effective at reducing N_2O emissions from cattle dung and urine, sheep urine, and swine slurry (Table 7). Assessment of the effectiveness of nitrification inhibitors on swine slurry was limited to Brazilian studies (Aita et al., 2014, 2015, 2019), which showed a mean reduction in swine slurry N_2O EF of 56% due to the addition of DCD (Table 7). In contrast, no significant reduction in N_2O EF was found for cattle slurry based on data collated from studies conducted in Australia, Chile, and the United Kingdom (e.g., Alfaro et al., 2018). Our analysis of inhibitor effectiveness included slurry that was either surface applied, banded, or injected into soil. There is growing interest in assessing the effectiveness of inhibitors where manures or slurries are banded or injected, given the risk of increased N_2O emissions from low-trajectory and injection methods, as discussed earlier. To date, testing of nitrification inhibitors for reducing N_2O emissions from slurry that is banded or injected has produced mixed results, with the negative correlation between soil temperature and inhibitor effectiveness identified as the primary factor explaining null results (e.g., Herr et al., 2020; Thorman et al., 2020).

Application of nitrification inhibitors to soil to target urine patches from grazing livestock was initiated in early 2000s (Di & Cameron, 2002), with studies now extending across several countries (e.g., Australia, Brazil, Canada, Chile, Ireland, New Zealand, and the United Kingdom). There appears to be a consistent response to nitrification inhibitors when applied to cattle urine, illustrated by a series of trials in New Zealand and the United Kingdom, where DCD reduced cattle urine N_2O emissions by, respectively, 49 and 46% (Chadwick et al., 2018; Gillingham et al., 2012). Our analysis of N_2O EF for cattle urine showed a similar mean reduction of 45% when treated with a nitrification inhibitor (n = 238; Table 7). However, as for inhibitor-treated manure, temperature affects the effectiveness of DCD to reduce N_2O emissions from urine. Seasonal studies conducted in subtropical climates showed that DCD sprayed onto urine patches was only effective at reducing EF in cooler autumn and winter seasons, when the mean temperature was 17 °C, with no significant reduction in the warmer spring and summer seasons (Simon et al., 2018). Under warmer tropical climates, DCD was ineffective at reducing N_2O emissions from urine patches (Mazzeto et al., 2015). Dicyandiamide has a half-life of 14 d at 30 ˚C mean soil temperature and 73 d at 10 ˚C (Kelliher et al., 2008), which probably explains why DCD is ineffective in tropical climates. The number of studies quantifying N_2O emissions from dung treated with nitrification inhibitors is small; however, our analysis of 39 observations suggested a mean reduction of 63% in N_2O EF for cattle dung. Again, temperature is a key variable, with temperate New Zealand studies showing a reduction (e.g., Cameron et al., 2014; de Klein et al., 2014), whereas Brazilian studies under a subtropical climate showed limited effectiveness (Simon et al., 2018).

The assessment of the effect of nitrification inhibitors through our analysis (Table 7) helps inventory compilers in countries that are currently using or are considering the use of nitrification inhibitors with potential Tier 1 adjustments. Furthermore, identifying and quantifying mitigation options such as nitrification inhibitors can provide agricultural researchers with opportunities to test these at their local scale. However, we agree with the conclusion reached by Thorman et al. (2020), who noted that the highly variable response to nitrification inhibitors creates a significant challenge for ensuring accuracy if they are included as viable mitigation strategies within national inventories. Further work is required to understand the influence of soil and climatic conditions.

4.3 | Issues of representativeness

The field database is dominated by studies conducted in Europe and Oceania (i.e., temperate wet climates), and therefore many of the recommended EF values presented in this study will be of direct use and relevance for these regions. However, our analysis has provided an update on EF values for generic climate regions and N sources. It is also encouraging to observe an increase in the number of EF studies (in particular, N_2O) conducted in other regions that represent a significant proportion of livestock production. For instance, over recent years the number of publications from the sub-Saharan African region and South America has improved our understanding of farming systems and associated GHG emissions. Sub-Saharan Africa is home to approximately 25% of the global livestock population, which in the last 60 years has increased by factors of 2.5–4 times for cattle, goats, and sheep (Butterbach-Bahl et al., 2020), and South America has the highest density of cattle of any continent (Robinson et al., 2014). There are some regions that are poorly represented in the database or not represented at all (e.g., India, Southeast and East Asia). We encourage more research and publication of findings from these under-represented regions, improving the representativeness of the database and the development and enhancement of EF values.

5 | CONCLUSIONS

Using the DATAMAN database, we have developed disaggregated NH_3 EFs for cattle and swine manures applied to land in wet climates and N_2O EF for cattle, sheep, and swine manure emissions in wet and dry climates. Because the underlying data were collated from multiple studies across several countries, these disaggregated EF values are at a scale greater than country-specific EF values. We also quantified reductions in NH_3 emissions from slurry applied to land of between 46 and 62% with low emissions application methods compared with broadcast application. Furthermore, the use of nitrification inhibitors reduced N_2O emissions in swine manure, cattle urine/dung, and sheep urine by 45–63%.

These improved and disaggregated EF values can be used by inventory compilers to improve the accuracy of national inventories and quantify the effectiveness of mitigation strategies where country-specific EFs do not exist. However, there are gaps within the current database, with some regions poorly represented (e.g., Asia, Africa, South America). We hope that in time, data will become more representative as we continue to include additional studies within the DATAMAN database from a wide range of agricultural systems that are practiced under a range of climates and regions.

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AUTHOR CONTRIBUTIONS

Tony J. Van der Weerden: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Writing-original draft; Writing-review & editing. Alasdair D.L. Noble: Data curation; Formal analysis; Investigation; Methodology; Writing-original draft; Writing-review & editing. Cecile A.M. de Klein: Conceptualization; Investigation; Methodology; Writing-original draft; Writing-review & editing. Nicholas Hutchings: Conceptualization; Investigation; Methodology; Writing-original draft; Writing-review & editing. Rachel E. Thorman: Conceptualization; Funding acquisition; Investigation; Methodology; Writing-original draft; Writing-review & editing. Marta A. Alfaro: Conceptualization; Funding acquisition; Writing-review & editing. Barbara Amon: Conceptualization; Writing-review & editing. Ignacio Beltran: Investigation; Writing-review & editing. Peter Grace: Writing-review & editing. Mélynda Hassouna: Conceptualization; Writing-review & editing. Dominika J. Krol: Conceptualization; Writing-review & editing. April B. Leytem: Writing-review & editing. Francisco Salazar: Conceptualization; Writing-review & editing. Gerard L. Velthof: Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Tony J. van der Weerden https://orcid.org/0000-0002-6999-2584
Alasdair Noble https://orcid.org/0000-0003-2292-8216
Cecile A. M. de Klein https://orcid.org/0000-0001-7840-0934
Nicholas Hutchings https://orcid.org/0000-0001-8794-5549
Rachel E. Thorman https://orcid.org/0000-0001-7175-2005
Marta A. Alfaro https://orcid.org/0000-0002-1881-4745
Barbara Amon https://orcid.org/0000-0001-5650-1806
Ignacio Beltran https://orcid.org/0000-0002-1062-1017
Peter Grace https://orcid.org/0000-0003-4136-4129
Mélynda Hassouna https://orcid.org/0000-0001-8994-9690
Dominika J. Krol https://orcid.org/0000-0003-0381-7895
April B. Leytem https://orcid.org/0000-0001-5976-402X
Francisco Salazar https://orcid.org/0000-0002-3794-7682
Gerard L. Velthof https://orcid.org/0000-0003-0838-5622

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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