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Meta-analysis of New Zealand's nitrous oxide emission factors for ruminant excreta supports disaggregation based on excreta form, livestock type and slope class.

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Abstract

Globally, animal excreta (dung and urine) deposition onto grazed pastures represents more than half of anthropogenic nitrous oxide (N_2O) emissions. To account for these emissions, New Zealand currently employs urine and dung emission factor (EF_3) values of 1.0% and 0.25%, respectively, for all livestock. These values are primarily based on field studies conducted on fertile, flatland pastures predominantly used for dairy cattle production but do not consider emissions from hill land pastures primarily used for sheep, deer and non-dairy cattle.

The objective of this study was to determine the most suitable urine and dung EF_3 values for dairy cattle, non-dairy cattle, and sheep grazing pastures on different slopes based on a meta-analysis of New Zealand EF_3 studies. As none of the studies included deer excreta, deer EF_3 values were estimated from cattle and sheep values. The analysis revealed that a single dung EF_3 value should be maintained, although the value should be reduced from 0.25% to 0.12%. Furthermore, urine EF_3 should be disaggregated by livestock type (cattle > sheep) and topography (flatland and low sloping hill country > medium and steep sloping hill country), with EF_3 values ranging from 0.08% (sheep urine on medium and steep slopes) to 0.98% (dairy cattle on flatland and low slopes). While the mechanism(s) causing differences in urine EF_3 values for sheep and cattle are unknown, the 'slope effect' on urine EF_3 is partly due to differences in soil chemical and physical characteristics, which influence soil microbial processes on the different slope classes.

The revised EF_3 values were used in an updated New Zealand inventory approach, resulting in 30% lower national N_2O emissions for 2017 compared to using the current EF_3 values. We recommend using the revised EF_3 values in New Zealand's national greenhouse gas inventory to more accurately capture N_2O emissions from livestock grazing.

Keywords: urine; dung; cattle; sheep; inventory; hill country

1. Introduction

Nitrous oxide (N_2O) is the third most abundant anthropogenic greenhouse gas (GHG), representing 6% of the total radiative forcing over the industrial era (Myhre et al. 2013). By comparison, carbon dioxide (CO_2) and methane (CH_4) represent, respectively, 64% and 17% of total radiative forcing (Myhre et al. 2013). Despite its low concentration of 328 ppb, N_2O has a significant effect on global warming as it has an atmospheric lifetime of ~120 years and is 265 times more potent than CO_2 (IPCC 2014) while also being a significant contributor to stratospheric ozone depletion (Myhre et al. 2013; Ravishankara et al. 2009). Grasslands worldwide, covering about 40.5% of the terrestrial area (52.5 million km^2, World Resource Institute 2000), emitted 2.2 Tg N_2O-N in 2006 (equal to 54% of agricultural N_2O emissions), of which 74% were derived from anthropogenic sources (Dangal et al. 2019). Animal excreta (dung and urine) deposition is the single largest source (54%) of annual N_2O emissions from grasslands averaged over 1961 to 2014, followed by manure application (13%) and nitrogen (N) fertiliser application (7%) (Dangal et al. 2019). Nitrification and denitrification are the dominant processes responsible for N_2O production in soils, although nitrifier-denitrification, co-denitrification and chemo-denitrification can also lead to N_2O formation given a suitable microbial community and environmental conditions (Hallin et al. 2018; Selbie et al. 2015).

The current Intergovernmental Panel on Climate Change (IPCC) guidelines for calculating national GHG inventories provide default emission factors for direct N_2O emissions from excreta deposited during livestock grazing (EF_{3PRP}; representing the percentage of N deposited being lost as N_2O from pasture, range and paddock). Values are disaggregated by animal type, where cattle, poultry and pigs have a default value of 2% of the N deposited, while sheep and ‘other animals’ have a value of 1% (IPCC 2006). However, there is a growing body of evidence that shows N_2O emissions are also affected by excreta type (dung vs urine). Several countries, for which N_2O emissions from excreta represent a significant proportion of the national inventory (e.g. UK, Ireland, New Zealand), have therefore recommended country-specific EF_3 values, disaggregated by excreta type (dung and urine) (Chadwick et al. 2018; de Klein et al. 2001; Krol et al. 2016; Luo et al. 2009a; van der Weerden et al. 2011; Zhu et al. 2019). Recently, the IPCC have published a refinement of the 2006 guidelines, where the default EF_3 values have been updated by including results from recent studies (IPCC, 2019). Excreta EF_3 values were disaggregated by livestock type (cattle vs sheep), excreta type (dung vs urine) and climate (wet vs dry). In New Zealand, EF_3 values for urine and dung are currently 1% and 0.25%, respectively; both have been implemented in the national agricultural greenhouse gas inventory (Ministry for the Environment 2019). The New Zealand values, applied to all major livestock classes (sheep, cattle and deer), are similar to the results from recent cattle excreta studies in the UK (urine and dung averaging 0.69% and 0.19%, respectively; Chadwick et al. 2018) and Ireland (urine and dung averaging 1.18% and 0.31%, Krol et al. 2016).

These New Zealand EF_3 values for urine and dung were calculated from a series of field trials primarily conducted on relatively fertile, flatland pastures (e.g. Carran et al. 1995; Muller et al. 1995; de Klein at al. 2003; Luo et al. 2009a). However, about one-third of New Zealand's 14.7 Mha of pastural land has been identified as grazed hill country (de Klein et al. 2009), where slope influences soil characteristics, pasture production, pasture N content, pasture intake by livestock, excreta deposition and soil conditions (e.g. soil bulk density, moisture and soil nutrient status) (Saggar et al. 1990a; MacKay et al. 1995; Luo et al. 2019). These factors can also affect N_2O production processes and emissions (Luo et al. 2019). Field trials conducted in hill country pasture sites over the past 10 years demonstrate that N_2O emissions and EF_3 values for sheep, non-dairy- and dairy-cattle excreta on hillslopes are generally lower than on flatter areas due to highly variable spatial differences in soil conditions (e.g. microbial biomass, soil moisture and fertility status) and climatic conditions (e.g. temperature and rainfall) across the slopes (de Klein et al. 2009; Hoogendoorn et al. 2013; Luo et al. 2013, 2016a, 2019; Saggar et al. 2015). An earlier meta-analysis confirmed that EF_3 values for livestock urine and dung deposited on medium (12 - 24°) slopes were significantly lower than those from low (0 - 12°) slopes (Kelliher et al. 2014). It is thus suggested that disaggregating EF_3 by slope class would provide a more accurate inventory of national N_2O emissions. Saggar et al. (2015) proposed a revision to New Zealand's agricultural greenhouse gas inventory structure that would account for the effect of urine and dung deposited by different livestock classes (non-dairy cattle, sheep and deer) onto different hill country slope classes on the N_2O emissions from livestock grazing hill country. The New Zealand EF_3 database used in the Kelliher et al. (2014) meta-analysis did not include EF_3 values for steep slopes as no results were available at the time. However, in recent years, field trials have begun to incorporate steep (> 24°) hill country slopes for determining dung and urine EF_3 values (Luo et al. 2016). The objectives of this study were to update the New Zealand EF_3 database with slope-based values and to determine the most suitable urine and dung EF_3 values for dairy cattle, non-dairy cattle and sheep grazing pastures on different slope classes based on a meta-analysis. As none of the studies included deer excreta, with deer EF_3 values were estimated from cattle and sheep values. We hypothesized that there would be significant differences in EF_3 due to livestock type, excreta type and slope class. This study will help to improve the accuracy of New Zealand's national GHG inventory for estimating N_2O emissions from livestock grazing.

2. Methods

2.1 Database description

The New Zealand N_2O emission factor database was first constructed for the earlier meta-analysis found in Kelliher et al. (2014) where data was compiled from journal publications and reports detailing field studies funded by the New Zealand Ministry for Primary Industries (MPI) for the purpose of developing country-specific N_2O emission factors. The database contained replicate-level cumulative N_2O emissions measured from N sources (e.g. cattle and sheep urine and dung, N fertiliser, dairy cattle effluent) and associated control treatments (nil N and nil water) applied to field plots situated largely on ryegrass/white clover pastures, representative across regions of New Zealand's dominant pasture species. Authors were contacted for replicate-level N_2O emissions data and other key data not included in publications and reports.

Following the approach of Kelliher et al. (2014), the database was updated for the current study. For our EF_3-specific meta-analysis, fertiliser studies from the original EF database were excluded. A similar approach was taken when the original EF database was expanded for a meta-analysis of fertiliser EF_1, where the excreta EF_3 data were excluded (van der Weerden et al. 2016). The updated EF_3 database contained field studies conducted from 2000 to 2017 across a range of soil types, climates, slopes, seasons, regions, and soil drainage classes. The additional data came from field studies reported either in journal publications (Cameron et al.

2014; de Klein et al. 2003, 2011, 2014; Hoogendoorn et al. 2008, 2016; Ledgard et al. 2014; Luo et al. 2008, 2013, 2015, 2019; van der Weerden et al. 2011) or as reports to MPI (de Klein et al. 2004; Hoogendoorn et al. 2013; Luo et al. 2009b, 2010, 2016, Sherlock et al. 2003a, 2003b). Again, authors were contacted for replicate-level emissions data and any missing key data.

Field studies conducted on contrasting topographies were grouped as either flatland or hill country. ‘Flatland’ is defined as large areas of flat fertile pastoral land typically represented as plains and undulating hills, where the slope is typically <12°. These landscapes largely support New Zealand’s dairy cattle production, while also providing suitable land for sheep, non-dairy cattle and deer production. Farmers will generally maintain soil fertility within the biological optimum ranges for pasture production (e.g. soil Olsen P test of 20-30 µg P/ml soil and soil pH of 5.8-6.0; Morton and Roberts, 2016; Morton, 2019; Roberts and Morton, 2016), given the relatively higher returns from these soils. While flatland pastures often contain N-fixing legumes (generally mixed ryegrass/white clover swards), strategic N fertiliser applications of between 30-50 kg N/ ha per application are commonly practiced to help minimise feed deficits (Roberts and Morton, 2016). ‘Hill country’ represents hill and high-country pastoral land where annual pasture dry matter production and stock numbers per hectare are lower than flatland. Hill country covers both the North and South Islands of New Zealand, whereas high country is defined as land over 700m altitude, only found in the South Island (Swaffield and Hughey, 2001). We have separated ‘hill country’ into three slope classes: low (0 - 12°), medium (12 - 24°) and steep (> 24°) slopes. Much of New Zealand’s sheep, non-dairy cattle and deer production are situated on hill country landscapes.

The dataset included data generated from field plot and lysimeter trials. Field plots typically had an area of 2 m^2, providing enough area for greenhouse gas emission measurements using static chambers (approximately 0.05 m^2) and soil sampling during the course of a field trial. Lysimeter trials consisted of large intact columns of soil (700 mm deep x 500 mm diameter) excavated from their natural field locations and enclosed in steel cylinders. For urine EF_3 studies, either real or synthetic urine was used. All studies included at least four replicate plots per treatment. Field trials averaged 173 days, with the duration of all but one study being equal to or greater than the

30-day threshold recommended by the IPCC (IPCC, 2019). A further criterion used for study inclusion was for N_2O fluxes and soil mineral N concentrations from the N source to return to background (control) levels (de Klein and Harvey 2015).

For the meta-analysis, EF_3 values were calculated at the replicate-level for each individual study using the following equation (de Klein and Harvey 2015):

$$EF_3 = \frac{\text{Excreta } N_2O - \text{Control } N_2O}{\text{N load}} \times 100\% \quad (1)$$

Where, EF_3 is the emission factor of an N source (dung or urine) (N_2O lost as % of N source applied); Excreta N_2O is the cumulative N_2O loss (kg N_2O-N/ha) from the N source (dung or urine); Control N_2O is the cumulative N_2O loss from the control treatment (kg N_2O-N/ha) and N load is the amount of N applied with the N source (dung or urine in kg N/ha).

2.2 Assessment of data suitability

To determine whether EF_3 values obtained from lysimeter studies and from synthetic urine application were suitable for the meta-analysis, the data were initially graphed and, where deemed necessary, analysed by testing the effect of trial method or urine type using the meta-analysis models described below. The rationale for determining whether lysimeter studies were suitable for inclusion relates to the potential effect of restricted lateral movement of urine-derived available N on N_2O EF_3 values. While others have included both lysimeter and field plot-derived data in EF_3 meta-analysis studies (e.g. IPCC 2019; López-Aizpún et al. 2020), we considered this assessment was necessary to remove any potential bias in the resulting EF_3 values. Similarly, the rationale for determining whether synthetic urine studies suitably represented the N_2O emissions from real urine relates to whether the inclusion of the former would bias the analysis. Synthetic urine has been compared to real urine by several workers, with some observing either lower (de Klein et al. 2003) or higher (Kool et al. 2006) N_2O emissions from synthetic urine. Previous meta-analyses have either included (IPCC 2019) or excluded (López-Aizpún et al. 2020) synthetic urine studies.

Furthermore, the field trials encompassed a wide range of nitrogen (N) loads. While field trials apply urine or dung in terms of g N/m^2, N loads are presented with units of ‘kg N/ha’. Given the uncertain effect of N load on EF_3 (de Klein et al. 2019), we analysed the dataset for any possible ‘N load effect’. A positive or negative effect of N load on EF_3 would most likely require excreta N load to be included in national inventory methodologies for estimating N_2O emissions from livestock grazing. Thus, N load was included in the models described below as a covariate and its effect assessed in the model.

2.3 Meta-analysis

To analyse the data, two generalized linear mixed models were fitted: one using log-transformed data and a Gaussian (or normal) distribution, and one using untransformed data with a Poisson distribution and, following standard theory, a logarithmic link function (McCullagh and Nelder, 1989). As there were negative and zero values in the dataset, log transformation was not possible for all values, so, prior to analysis, a small positive offset was added to all data points, which was equal to the lowest negative value plus 0.0001. The Poisson model required the same adjustment to eliminate negative and zero values. For both models, excreta type (urine and dung), livestock type (dairy cattle, non-dairy cattle and sheep), topography (flatland, low slope, medium slope and steep slope) were fitted as fixed effects while site was included as a random effect. Excreta type was included because the form of excreta-N in urine and dung differs (Krol et al. 2016; Luo et al. 2019), which affects the magnitude of EF_3, as noted earlier. Livestock type was included due to its influence on the amount of dung and urine per excretion event (Selbie et al. 2014), as well as lower soil compaction from sheep due to lower body liveweight compared with cattle (Houlbrooke et al. 2011). The models were used to group animal types and topographies for dung and urine excreta. All analysis was carried out using the R statistical package (R Core Team 2017). The emission factors were arithmetic means of each identified group.

2.4 Influence of topography on EF_3

The earlier meta-analysis of New Zealand data by Kelliher et al. (2014) noted that average urine and dung EF_3 values for low and medium slopes were significantly different. Given the larger dataset used in the current study, we hypothesised a similar ‘slope effect’ on EF_3 may occur. Therefore, available soil variables were collated to investigate potential drivers of a ‘slope effect’ on EF_3. Soil variables included soil bulk density (Mg/m^3), soil pH, soil Olsen P (a measure of the available P supply to plants; µg/ml dry soil), soil organic C (%), soil total N (%) and volumetric water content (v/v) averaged over 30 days following excreta deposition. These soil variables were chosen based on literature suggesting they are influential drivers of N_2O production and emission (Baggs et al. 2010; Bhandral et al. 2007; Bremner, 1997). Soil water content is inversely proportional to soil oxygen and is thus a readily-determined proxy for soil oxygen level. The most commonly used proxy for soil oxygen status is soil water filled pore space (WFPS) (Linn and Doran, 1984; Dobbie and Smith, 2001; van der Weerden et al. 2017). However, a recent analysis of key drivers influencing dairy cattle urine EF_3 revealed that volumetric water content (v/v), averaged over 30 days following urine deposition, best described the variation in EF_3 across 70 field studies (van der Weerden et al. unpubl. data). It has been suggested that volumetric water content is potentially a better descriptor of nitrification and denitrification-induced N_2O emissions compared to WFPS, as it directly accounts for variation in soil bulk density (Farquharson and Baldock 2008). We therefore used this metric for our analysis. We included soil Olsen P content as a proxy for soil fertility status that may reflect soil microbial activity (Luo et al. 2011). Data on all these soil variables were not available for all hill country sites, and therefore our analysis may only partially explain any observed ‘slope effect’.

2.5 Implications for the national agricultural N_2O inventory

Following the meta-analysis and determination of new EF_3 values for different excreta types and slope classes, national direct N_2O emissions from excreta deposition were calculated for three years (1990, 2005 and 2017). These years were selected as representing the baseline year for national GHG inventory reporting (1990; Ministry for the Environment 2019), the most recent published national inventory (2017; Ministry for the Environment 2019), and an approximate midpoint between these two years (2005). There are no field results for deer excreta; therefore, we used the average of the sheep and non-dairy cattle EFs given the average live body weight of deer is close to the average of sheep and non-dairy cattle. As deer excreta only accounts for 2-3% of the national N excreta, this assumption has little impact on the total N_2O emission. The total amount of dung and urine N excreted by year and by animal species was taken from the national agricultural inventory model (data provided by MPI).

Dairy cattle typically graze flatland areas, which are generally fertile pastoral plains with slopes typically <12°. For sheep, non-dairy cattle, and deer we used survey data from Beef + Lamb New Zealand that divided animal numbers into 17 different regional farm classes, where each class represented a similar geography and farm management. The proportion of low, medium and steep lands was also given for each farm class. For each stock type, we allocated the total urine and dung N between farm classes in proportion to the number of animals in each class. Then for each farm class, the nutrient transfer model described in Saggar et al. (2015) was used to allocate dung and urine N between low, medium, and steep slopes based on the fractional land area in each slope category for that farm class. Briefly, as animals prefer to spend more time on flatter land, the excretal N deposits onto each slope class is not proportional to the area of each slope class. To successfully account for the effect of topography-driven spatial variability of N excretion rates, a mass balance approach was included in the model to explain the accumulation or depletion of nutrients in soils by considering animal-associated nutrient return through variable excretal deposition across the slopes. The model was developed from New Zealand hill country sheep grazed pasture data collected from Ballantrae hill country farm in the lower North Island, New Zealand (Saggar et al. 1990a) and tested at Whatawhata hill country farm in the upper North Island, New Zealand (Saggar et al. 1990b). It should be noted that sheep, non-dairy cattle, and deer were not assigned to a single slope class (it was assumed they could move between slope classes), with the nutrient transfer model taking account of animal behaviour with relatively more time, and therefore excreta deposition, on the lower slopes. Employing the nutrient transfer model in the national GHG inventory disaggregates activity data (urine and dung N load) by slope class, with proportionately more urine and dung N being ‘deposited’ onto lower slopes than on steeper slopes due to animal behaviour. The mean percentage of dung and urine deposition by sheep, non-dairy cattle, and deer are shown in Table 1. As dung tends to roll down slopes, its nutrient transfer values are slightly higher (Saggar et al. 2015).

3. Results

3.1 Database description

The updated database contains 139 field studies supplying 1217 replicate-level EF_3 values, representing 781 (64%) for urine and 436 (36%) for dung (Table 2). An examination of the dataset showed that the distribution of EF_3 values across the topographies was biased towards flatlands, which accounted for 515 (42%) of the datapoints. On hill country terrain, low slope data dominated the dataset, at 382 (31%), followed by medium and steep slopes, at 240 (20%) and 80 (7%) EF_3 values, respectively. Furthermore, on flatland, no data existed for non-dairy cattle dung and only one study contained non-dairy cattle urine data (Table 2). The distribution of EF_3 values across the topography classes is also shown (Table 2).

The EF_3 dataset is reasonably representative of the actual distribution of dairy cattle, non-dairy cattle, sheep and deer excreta N across different topographies in New Zealand, as indicated by a comparison of dung and urine EF_3 data with this distribution (Fig. 1). For this comparison, the distribution of non-dairy cattle, sheep and deer N excreta was calculated using the nutrient transfer model (Saggar et al. 2015), applied to the percentage of low, medium and steep land used for these livestock classes in 2017-18 (source: Beef & Lamb Economic Farm Survey), with ‘low slope’ including any stock on ‘flatland’. Although dairy cattle typically graze flatland fertile plains (Ministry for the Environment 2019), dairy excreta treatments were included in several hill country studies (e.g. Luo et al. 2013) to provide a reference for comparison with non-dairy cattle livestock. However, the inclusion of the dairy cattle excreta EF_3 data from these hill slope studies only represents 2% of the EF_3 dataset.

Similar to Kelliher et al. (2014), ‘season’ was based on the month of the 15th day of the trial: December, January, and February for summer, March, April and May for autumn, June, July and August for winter and September, October and November for spring. Winter contained the largest number of EF_3 values (447, or 37% of the dataset) and covered the greatest range of N sources (livestock type and excreta type). Autumn was the next best represented season, followed by spring. The least represented season was summer, with 132 EF_3 values (11% of the total dataset) limited to cattle excreta only, and mainly on low slopes or flatland, apart from 40 replicate-level EF_3 values for non-dairy cattle excreta on medium slopes. All data was log-transformed prior to statistical analysis – see visual representation of data in Supplementary file (Fig. S1).

The field trials were conducted in seven regions across New Zealand, from the north (Northland) to the south (Southland) (Fig. 2, Table 3). While the dataset does not fully represent the national distribution of livestock classes and numbers, we consider the field study locations were reasonably representative for the purposes of generating national EF_3 values. It should be noted that the national distribution of livestock classes and numbers is ever-changing, making it somewhat challenging to ensure the EF_3 dataset structure is representative of livestock activity at the regional and national scale.

3.2 Assessment of data suitability

Emission factors derived from lysimeter studies were restricted to flatland trials and included both dairy cattle dung and dairy cattle urine N sources. EF_3 values from 44 lysimeter trials were evenly distributed amongst plot-based field trials and were all included in the meta-analysis. See Supplementary file Fig. S2 for further information.

The use of synthetic urine was restricted to trials conducted on flatland and low slope sites. The synthetic urine EF_3 data from flatland trials were evenly dispersed throughout the real urine EF_3 dataset. However, the results from synthetic urine applied to low slopes appear to be at the upper end of urine EF_3 values obtained using real urine collected from dairy cattle and sheep. An analysis of the entire low slope urine dataset for dairy cattle and sheep showed synthetic urine had no significant effect on EF_3 ($P > 0.05$) and we therefore retained the synthetic urine EF_3 data for the meta-analysis. See Supplementary file Fig. S3 for further information.

There was no effect of N load on EF_3 when all data were pooled ($P = 0.85$) and was generally the same when data were separated into livestock class (dairy cattle, non-dairy cattle and sheep) and excreta type (urine and dung), apart from beef urine. For this latter N source, there was a significant N load effect on EF_3 ($P < 0.05$). However, the range of N loads used for beef urine field trials ranged from *ca* 200 to 600 kg N/ha (Table 4). Because the pooled data showed no N load effect on EF_3, data analysis proceeded without including the effect of N load. See Supplementary file Fig. S4 for further information.

3.3 Meta-analysis

Results from the two models were similar in all analyses, with slight variations in the level of significance between groups in certain instances (see supplementary file Tables S1-S4). The results reported here are from the Gaussian linear mixed model. As urine EF_3 values were significantly greater than dung EF_3 values ($P < 0.001$), we disaggregated urine and dung data for subsequent analyses.

3.3.1 Dung

The analysis showed there was no significant effect of livestock type or slope class on dung EF_3 values ($P = 0.60$ and $P = 0.90$, respectively), and the dung EF_3 values were therefore pooled to a single value of 0.12% (Tables S1 and S2).

3.3.2 Urine

The analysis showed that urine EF_3 was significantly influenced by livestock type ($P < 0.05$), with significantly lower values for sheep urine compared with dairy and non-dairy cattle urine (Table S3). We therefore combined dairy and non-dairy cattle urine into a single category and treated sheep urine separately. The results also showed urine EF_3 was influenced by topography (Tables S4 and S5). Specifically, both the Gaussian and Poisson distribution models supported grouping flatland and low slope urine EF_3 values into a single category, distinct from medium and steep slope urine EF_3 values.

On flatland and low slopes, sheep urine EF_3 was 0.50%, which is approximately half of cattle's EF_3 value of 0.98% (Table 5). On medium/steep slopes, sheep urine EF_3 was 0.08%, approximately one quarter of the cattle EF_3 value of 0.33%. The effect of slope was evident, with cattle urine EF_3 on medium/steep slopes being one third of that for flatland and low slopes, and the sheep urine EF_3 for medium/steep slopes being only one sixth of that for flatland and low slopes. Dung EF_3 (0.12%) was lower than urine EF_3 for all combinations, except for sheep on medium/steep slopes, which were approximately 50% higher than that for sheep urine (Table 5).

3.4 Influence of topography on urine EF_3

Soil variables from field trial sites were collated and analyzed to improve interpretation of the observed 'slope effect' on urine EF_3. Our analysis of available soil properties (soil bulk density, soil pH, soil Olsen P, soil organic C, soil total N and volumetric water content (v/v) averaged over 30 days following urine deposition) showed that soil bulk density was significantly lower on low slopes compared to medium and steep slopes ($P < 0.05$) (Figure 3). In contrast, soil Olsen P, soil organic C, soil total N and volumetric water content were all significantly higher on low slopes compared to steeper slopes ($P < 0.05$). Soil pH did not vary significantly across slope classes (Fig. 3).

3.5 Implications for the national N_2O inventory

To assess the impact of updating EF_3 values for flatland and hill country soils on the national N_2O inventory, we compared N_2O emissions using country-specific livestock EF_3 values (EF_3 = 1% and 0.25% for urine and dung respectively; Ministry for the Environment, 2019) to emissions estimated using mean values from the meta-analysis results herein (Table 4).

Adopting the revised EF_3 values reduced the calculated total direct N_2O emissions for 1990, 2005 and 2017 (Fig. 4). Calculated total direct N_2O emissions from livestock grazing in 1990, 2005 and 2017 were 44%, 37% and 30% lower than those based on the current EF_3 values. Nitrous oxide emissions from dairy cattle grazing flatland pastures were 6% less than those based on current EF_3 values for all three years. For non-dairy cattle and sheep grazing on hill country, calculated direct N_2O emissions were, respectively, ~34% and ~66% less than those based on current EF_3 values for all three years. The reduction in calculated emissions from deer were between sheep and non-dairy cattle, at *ca* 50% of those based on the current EF_3 values.

When using country-specific EF_3 values of 1% (urine) and 0.25% (dung) for all livestock species, total N_2O emissions in 2005 and 2017 respectively increase by 12% and 8% compared with 1990. However, using revised livestock-specific EF_3 values show that total N_2O emissions in 2005 and 2017 were 28% and 33% higher compared to the 1990 estimates. This relatively larger increase in emissions since 1990 reflects sheep emissions accounting for a much smaller proportion of the total emissions compared to dairy cattle N_2O emissions which have nearly doubled since 1990.

While low slopes represented only 20% of pastoral hill country, the nutrient transfer model estimated that around 57% of the excretal N was deposited on this low slope area (Saggar et al. 2015). Based on the revised EF_3 values and the nutrient transfer model, low slopes represented 80% of the calculated total direct N_2O emissions (Fig. 5).

4. Discussion

The findings of this study corroborate results of an earlier meta-analysis (Kelliher et al. 2014), showing a significant difference in EF_3 values between cattle and sheep, low and medium slopes, and urine and dung. The New Zealand agricultural GHG inventory currently employs single urine and dung EF_3 values of 1.0% and 0.25%, respectively, for all livestock (Ministry for the Environment, 2019). Our meta-analysis of EF_3 data from New Zealand provides a significant update to the previous analysis (Kelliher et al. 2014) by nearly doubling the number of replicate-level dung and urine data (from n=691 to 1217) and hill country data increasing almost three-fold (from n=252 to 702). This expanded dataset now includes EF_3 data collected from sheep and beef cattle trials conducted on steep slopes, providing an opportunity to revise and disaggregate

EF_3 values based on topography for New Zealand's agricultural N_2O inventory. While the distribution of EF_3 values is relatively representative of the distribution of excreta N across different topographies, the locations of field studies do not represent all New Zealand's pastoral soils, climates and topographies. However, we believe that they provide a sufficient geographical spread, thereby improving the accuracy of the agricultural inventory relative to the current methodology.

4.1 Excreta type

The updated analysis confirmed the earlier results from Kelliher et al. (2014) that dung EF_3 is significantly lower than urine EF_3. For example, Kelliher et al. (2014) reported dairy dung and urine deposited onto flatland (= 'lowland') pastures have mean EF_3 values of, respectively, 0.23 and 1.16%, while sheep urine and dung on flatland pastures have mean EF_3 values of, respectively, 0.08% and 0.55%. Similar differences between dung and urine EF_3 were found on hill country slopes, with Kelliher et al. (2015) reporting beef dung and urine EF_3 values of, respectively, 0.06% and 0.32% on medium slopes. The current study also showed that livestock class and topography had no significant effect on dung EF_3, and therefore a revised single country-specific value of 0.12% is recommended for New Zealand. The current country-specific dung EF_3 value of 0.25% was based on 128 replicate-level values from New Zealand and a review of international literature (Luo et al. 2009a). Our value of 0.12% proposed here is based on 436 replicate-level EF_3 values for cattle and sheep dung measured from representative pastoral sites over the past *ca* 10 years.

The difference in dung and urine EF_3 values observed herein is supported by international studies conducted in Europe, Africa and South America (Bastos et al. 2020; Chadwick et al. 2018; Hoeft et al. 2012; Krol et al. 2016; Pelster et al. 2016; Simon et al. 2018 and Sordi et al. 2014). Average cattle dung EF_3 values reported by these workers ranged from 0.1% to 0.31%, while average urine EF_3 values ranged from 0.26% to 1.18%. For sheep, average dung EF_3 values ranged from 0.03% to 0.09% while average urine EF_3 values ranged from 0.21% to 0.48%. This difference in dung and urine EF_3 values is supported by current understanding of differences in chemical and physical properties of dung and urine. The urine N loading rate often exceeds the N requirements of pasture, with the excess being vulnerable to loss (Selbie et al. 2015). The urea contained in urine is rapidly hydrolysed to mineral N available for nitrification and denitrification, leading to relatively high N_2O emissions (Luo et al. 2019). In contrast to urine, there is significantly less mineral N in dung (Krol et al. 2016, van der Weerden et al. 2011). For example, van der Weerden et al. (2011) observed that, on average, only 7% of total N in sheep and cattle dung was present as ammoniacal-N, while urine typically contained >90% available N (mainly as urea; Selbie et al. 2015). With typical loading rates of 700 and 1000 kg N/ha for urine and dung, respectively, these percentages equate to loading rates of readily-available N of >630 and 70 kg N/ha respectively. This partly explains lower rates of soil N transformation beneath dung pats compared to urine patches. Temporary N immobilisation during C decomposition in dung may explain the often-observed delay in N_2O emissions (van Groenigen et al. 2005). Subsequent mineralization of organic N is potentially utilized by pasture, which limits the buildup of excess ammonium and nitrate in the soil, thereby restricting nitrification and denitrification activities (van der Weerden et al. 2011).

Urine infiltrates rapidly into soil while dung tends to remain on the soil surface where it slowly decomposes. Rainfall or irrigation can aid the transport of dung below the soil surface. However, under dry weather conditions, crusting of dung may affect rates of N infiltration into soil, thereby restricting interaction with soil properties such as organic C and pH and the soil microbial community (van der Weerden et al. 2011, Zhu et al. 2018, 2019). This limited interaction between dung and soil, relative to urine, may partly explain why there was no slope effect on dung EF_3. While we observed a ‘slope effect’ on urine EF_3, it was actually a reflection of differences in soil properties across slopes that impacted N_2O emissions from urine (see discussion below). We suggest that underlying soil properties interact less with dung compared to urine, thereby reducing the influence of any apparent ‘slope-effect’ on dung N_2O emissions and EF_3.

4.2 Influence of livestock type on urine EF_3

Our analysis showed that cattle urine EF_3 was double that of sheep urine EF_3 on flatland and low slopes, while the difference was four-fold on medium to steep slopes. Thus, livestock type significantly influenced urine EF_3 values, which supports the need to disaggregate emissions from sheep and cattle urine. This is in line with the current IPCC guidelines, where cattle excreta have an EF_3 value twice that of sheep excreta (2% vs 1%, respectively; IPCC 2006). However, compared with the current IPCC values, our values are substantially lower, which corroborates other international studies that reported lower values than the current IPCC defaults (Chadwick et al., 2018; Krol et al. 2016; Pelster et al. 2016; Simon et al. 2018; Thomas et al. 2017; Voglmeier et al. 2019). The 2019 refinement of the 2006 IPCC guidelines has lowered EF_3 values, with default cattle and sheep urine EF_3 values of, respectively, 0.77% and 0.39% for wet climates being proposed (IPCC 2019). It is noteworthy that New Zealand is classified as having a wet climate.

The difference in EF_3 values between cattle and sheep could be due to differences in N loading rate and/or urination volume and urine patch size. The amount of N deposited or the “N loading rate” in a urine patch is a function of the N concentration of the urine, the urine volume excreted, and the surface area receiving urine (Selbie et al. 2015). Our meta-analysis showed that the N loading rate (kg N/ha) did not influence EF_3. A similar conclusion was reached in a recent review of N_2O emissions from deposited livestock urine (de Klein et al. 2019). New Zealand field studies typically use sheep and cattle urine volumes per patch area of 4 L/m^2 (150 ml applied to 0.0375 m^2) and 10 L/m^2 (490 ml applied to 0.049 m^2), respectively (e.g. de Klein et al. 2003; Luo et al. 2013; van der Weerden et al. 2011). The effect of sheep urine volume and urine patch size on cumulative N_2O emissions and EF_3 was examined in a study conducted by Marsden et al. (2016). Using either a low or high N concentration (4 and 16 g N/L), sheep urine was applied to a relatively moist pastoral soil (volumetric water content of 0.46 cm^3/cm^3) as either a single large patch (250 ml applied to 0.05 m^2; equivalent to 5 L/m^2) or as four small urine patches (62.5 ml applied to 0.0125 m^2; also equivalent to 5 L/m^2). For the low urine N concentration, EF_3 values were similar when calculated from cumulative N_2O emissions measured from a single large urine patch versus the sum of four small urine patches. However, for the high urine N concentration plots, EF_3 values were significantly greater for the four small urine patches compared to a single large patch. Marsden et al. (2016) found little to no effect of urine patch size on pasture biomass production and N uptake. The sheep and cattle urine N concentrations used in most New Zealand studies lie within the values used by Marsden et al. (2016), 6 - 8 g N/L (NZ data not shown). From an agronomic/soil process viewpoint, we expect the sum of four small urine patches may lead to greater N uptake by pasture compared to that of a single large urine patch due to the increased volume of soil and pasture roots having access to the urine-affected soil due to a higher surface to volume ratio.

Given our analysis showed that sheep urine EF_3 was significantly lower than cattle urine EF_3, further research is required to elucidate drivers of this difference. We support the suggestion made by Marsden et al. (2016) for repeated studies conducted under different environmental conditions, but also to examine the effect of typical cattle and sheep urine volumes, either by expanding the experimental design and/or conducting mechanistic modelling.

Another possible driver worthy of investigation is physiological differences in the digestion of forages by sheep and cattle, which may affect subsequent urine characteristics. López-Aizpún et al. (2020) proposed that the differences in sheep and cattle urine EF_3 may relate to differences in urine constituents other than the urine N content, which could be driven by diet (Dijkstra et al. 2013).

4.3 Influence of topography on urine EF_3

The effect of slope on urine EF_3 is thought to be due to a combination of reduced soil fertility and soil moisture on steeper slopes relative to gentler slopes (Luo et al. 2013). Our finding of lower soil bulk density (but higher N_2O emissions) on gentle slopes compared with medium and steep slopes, is a somewhat unexpected finding as results from previous studies suggest that increasing soil bulk density generally increases N_2O emissions and EF values (Bhandral et al. 2007; van Groenigen et al., 2005) due to reduced oxygen availability. Soil bulk density data were available for most sites (95%) and are therefore reasonably robust. However, our analysis also showed that many other properties that often show a positive relationship with N_2O emissions were significantly higher on low slopes (e.g. soil organic C, soil N and soil water content). It is possible that the lower bulk density values for low slopes reflect higher organic C content, which, together with other soil properties, appear to have outweighed the effect of bulk density on N_2O emissions.

Although soil P does not directly affect N_2O emissions under C-limited soil conditions (e.g. O'Neill et al. 2020), higher Olsen P levels can be an indicator for soil fertility status in legume-based New Zealand pastures, and therefore may be associated with labile N and C supply which influence soil microbial processes. The suggestion of a relationship between soil fertility and labile N and C supply is partially supported by the significantly greater soil organic C and total N content on low slopes. Indeed, greater nitrifying and denitrifying enzyme activity and higher abundance of soil microbial functional groups have been measured in higher fertility low slopes compared to lower fertility medium slopes (Letica et al. 2006; Zhong et al. 2016). Given the importance of nitrification in supplying substrate for denitrification, N_2O emissions could be expected to vary with slope (Luo et al. 2013). Nitrous oxide emissions and EF_3 values generally increase directly with soil water content (Dobbie and Smith, 2001; van der Weerden et al. 2017). Our data suggests medium and steep slopes have lower soil water content than gentle slopes, which will influence the oxygen status and therefore nitrification and denitrification processes. While data were not available for all sites, our analysis provides information on potential drivers explaining the observed 'slope effect' on urine EF_3.

Recent studies from the UK support the use of lower emission factors for extensively grazed 'uplands and hill areas' compared to intensively grazed pastures (Marsden et al. 2018; 2019). Marsden et al. (2018) measured EF_3 values from -0.02% to 0.08% for real and synthetic sheep urine deposited onto a semi-improved upland mineral soils in North Wales in spring and autumn. The trial sites had a 13% gradient (7° slope), which lies within New Zealand's 'low slope' category. The authors noted that these values are lower than UK-specific cattle urine value of 0.69% (Chadwick et al. 2018), which would be due to different climates, soils, vegetation, stocking density and, as discussed above, livestock type (Marsden et al. 2018). Their range of values for urine from sheep grazing a 'low slope' (-0.02% to 0.08%) is much lower than the proposed value of 0.50% for New Zealand (Table 4), with the difference likely reflecting some of the factors listed above i.e. climate, soil and vegetation. Marsden et al. (2019) measured N_2O emission factors for urine deposited onto upland peat soils of < 0.01% and suggested that the UK may wish to adopt an inventory approach separating lowland, upland and hill areas, akin to New Zealand's proposed structure. Their study also indicated that low nitrification rates, possibly due to low soil pH and/or high soil water content, were the most likely reason for low EF_3 values in upland organic soils, as EF_3 increased to 0.69% when NO_3^- and glucose were added to the soil. It is worth noting that the peat soils used in their study had soil pH levels of 4.4. In contrast, New Zealand's hill country is on mineral soils with a soil pH between 5 and 6 (Morton 2019). The field sites used for our EF_3 studies are representative, with soil pH generally between 5.2 and 6.0 (see Fig. 3).

Dung EF_3 was lower than urine EF_3 for all combinations, except for sheep on medium/steep slopes, where it was approximately 50% higher than that for sheep urine. This was probably due to lower microbial activity on steep sloping soils (Zhong et al. 2016) that results in lower rates of nitrification and consequently lower N_2O emissions from urine. As dung provides additional organic C, denitrification rates may have been higher under the dung pats than under the urine patches, thereby resulting in higher N_2O emissions.

4.4 Implications for the national N_2O inventory

An inventory methodology that can account for the effect of slope on both EF_3 values as well as on the transfer of nutrients will improve the accuracy of N_2O emission estimates from dung and urine for New Zealand hill country. Based on New Zealand's current inventory approach, direct N_2O emissions from excreta deposition in 2017 were 18.2 Gg N_2O (Ministry for the Environment 2019), representing 76% of direct N_2O emissions from agricultural soils and 14% of GHG emissions from the agricultural sector. New Zealand's 2017 N_2O emissions from urine and dung deposited onto soil increased by 7% since 1990 primarily due to a 90% increase in the dairy cattle population over this period, while sheep, non-dairy cattle and deer populations have reduced by 53%, 21% and 14%, respectively (Ministry for the Environment 2019).

Applying the updated New Zealand inventory approach for three years (1990, 2005, 2017) showed that the impact of the revised EF_3 values on calculated N_2O emissions varied between years. For instance, in 1990, the estimated N_2O emissions based on the revised EF_3 values were *ca* 44% of those based on the current approach. For 2005 and 2017 the estimated emissions were reduced by 37% and 30%, respectively (Fig. 3). The reduced impact of the revised EF_3 values over time (from 1990 to 2017) is due to the increasing influence of the dairy cattle population as a proportion of total livestock excreta deposited onto pasture, thereby offsetting some of the reduced N_2O emissions as a result of the lower (sheep and non-dairy cattle) hill land EF_3 values.

On average, low slopes represent only 20% of pastures grazed by sheep, non-dairy cattle and deer. However, these low sloping pastures represent 80% of direct N_2O emissions from excreta deposited by these livestock types. These values are based on land use data from 2017 (Fig. 5), however the same 80:20 ratio was found for 1990 data (data not shown). Thus, low slopes could be regarded as ‘critical source areas’ (CSAs) of direct N_2O emissions, a concept discussed for water quality considerations, where CSAs are considered as small areas of a farm or catchment that account for a disproportionately large amount of contaminant loss such as phosphorus (McDowell et al. 2019). Any efforts to apply technologies and practices to mitigate direct N_2O emissions from sheep, non-dairy cattle and deer grazing may, therefore, want to focus on grazed low slopes.

The New Zealand agricultural greenhouse gas inventory structure already includes a nutrient transfer model to account for livestock grazing and excretion behaviour (Saggar et al. 2015). We recommend applying the disaggregated EF_3 values (presented herein) to the national inventory to improve the accuracy of N_2O emission estimates for grazing livestock.

4.5 Limitations of the analysis

We have identified three key limitations of our database and the meta-analysis. Firstly, the significant N load effect on EF_3 observed for non-dairy cattle urine was possibly due to the limited N loads in the trials, which ranged from 207 to 589 kg N/ha. Nitrogen loads used for dairy urine field trials ranged from 367 to 1130 kg N/ha, which better represents reported ranges in N loads for cattle (200 – 2000 kg N/ha; Selbie et al. 2015). We therefore suggest additional experimental data using a wider range of N loads would aid in confirming whether an N load effect exists for non-dairy cattle urine.

Secondly, there is potential to improve the distribution of EF_3 data with respect to livestock type, excreta type, topography, season and region/soils/climate. Non-dairy cattle and sheep urine data for low slopes is under-represented (Fig. 1). Furthermore, seasonal distribution of the data is unbalanced, with only 10% (132/1218) of replicate-level EF_3 values coming from summer measurements (Table 1). Of these summer values, none relate to sheep excreta. Therefore, we recommend future EF_3 studies focus on non-dairy cattle and sheep urine deposited onto summer grazed pastures, including rain-fed and irrigated low sloping environments.

Thirdly, we found that data were not available for all field studies in order to explore potential drivers of the observed ‘slope effect’. We encourage future field studies, both within and outside New Zealand, to measure key urine, climate and soil variables (Buckingham et al. 2014; López-Aizpún et al. 2020). In addition to characterizing the dung and urine, including urine constituents, future studies should measure rainfall, temperature, soil bulk density, soil pH, soil total N and organic C and soil water content. Proxies for soil nutrient cycling (for example, in our case, Olsen P) and/or soil microbial activity should also be considered for inclusion. Analysis of diverse, large datasets will aid our understanding of N_2O emissions and associated EF_3 values for excreta deposited on contrasting soils and topographies under different climatic conditions.

Finally, there is also a limitation of the analysis relating to the assessment of the implications on the national N_2O inventory, which uses the nutrient transfer model to estimate the distribution of animal excreta across different slope classes. Although this model is based on only one study on the effect of slope on dung deposition, Saggar et al (2015) concluded that urine deposition is likely to follow similar patterns. We recommend further field studies are conducted to improve our understanding of the transfer of nutrients via dung and urine deposition on different slopes by grazing livestock.

5. Conclusions

Our meta-analysis of an expanded N_2O EF_3 database revealed that the current single EF_3 value for livestock dung should be reduced from 0.25% to 0.12%, while the current urine EF_3 value for urine should be disaggregated by livestock type (cattle, deer and sheep) and topography (flatland and hill country with low, medium and steep slopes). Disaggregated EF_3 values of 0.08% (sheep urine on medium and steep slopes) and 0.98% (dairy cattle on flatland and low slopes) should be used. We recommend implementing revised EF_3 values in an updated version of New Zealand's national greenhouse gas inventory that accounts for nutrient transfer by grazing livestock. This change will provide a more accurate accounting of N_2O emissions from New Zealand's grazing livestock.

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Figure captions

Fig. 1. Distribution of livestock excreta (% of total N excreted) in 2017 (Ministry for the Environment, 2019) and EF_3 data (% of total dataset, n=1218 values). Non-cattle, sheep and deer excreta distribution based on proportion of land area by slope class for 2017-18 (source: Beef & Lamb New Zealand Sheep and Beef Farm Survey) and nutrient transfer model (Saggar et al. 2015).

Fig. 2. Location of regions used for EF_3 field trials

Fig. 3. Pre-treatment soil properties (0-7.5 cm depth) measured at cattle and sheep EF_3 field sites on low, medium and steep slopes. Each black marker represents a single field site, with the box plot representing the median (solid black line), 25th and 75th percentile (lower and upper limits of box, respectively), and 95% confidence interval (upper and lower whiskers). Note that the soil properties were not measured at all field study sites, with degree of representation shown on the right hand side.

Fig. 4. Change in national N_2O emissions (Gg N_2O/annum) from dairy cattle, non-dairy cattle, sheep and deer for 1990, 2005 and 2017, estimated using livestock population data and current EF_3 values (left) and revised EF_3 values proposed herein (right).

Fig. 5. Proportion of land area (source: Beef + Lamb Economic Farm Survey), excretal N (via nutrient transfer model; Saggar et al. 2015) and N_2O emissions by hill slope category for sheep, non-dairy cattle and deer farms in 2017.

Table 1 Allocation of dung and urine depositions across slope categories (mean of sheep, non-dairy cattle, and deer; modified from Saggar et al. 2015).

Slope	Sheep, non-dairy cattle, and deer		Dairy cattle
	Mean % dung deposition	Mean % urine deposition	Mean % dung and urine deposition
0–12°	61	55	100
12–24°	30	31	
>24°	9	14	

Table 2 Number of replicate-level EF_3 values for each N source, topography class and season.

N source	Topography class	Autumn	Winter	Spring	Summer	Total
Dairy cattle urine	Flatland	128	105	88	12	333
	Low	34	34	28	20	116
	Medium		20			20
	Steep					
Dairy cattle dung	Flatland	14	34	36		84
	Low		26		20	46
	Medium		20			20
	Steep					
Non-dairy cattle urine	Flatland		8			8
	Low		20		20	40
	Medium	10	30		20	60
	Steep	10	10			20
Non-dairy cattle dung	Flatland					
	Low	20	28	8	20	76
	Medium	10	30		20	60
	Steep	10	10			20

Sheep urine	Flatland	8	8	20		36
	Low	24		44		68
	Medium	30	10	20		60
	Steep	10	10			20
Sheep dung	Flatland	10	16	28		54
	Low	20	8	8		36
	Medium	10	10			20
	Steep	10	10			20
	Total Flatland	160	171	172	12	515
	Total Low	98	116	88	80	382
	Total Medium	60	120	20	40	240
	Total Steep	40	40			80
Total		358	447	280	132	1217

Table 3 Distribution of EF_3 values by N source and region.

N source	North	Wai	HB	Man	Cant	Otago	South	Total
Dairy cattle urine	10	209	31	44	56	109	10	469
Dairy cattle dung	10	50	5	21	14	50		150
Non-dairy cattle urine	10	30	20	38		30		128
Non-dairy cattle dung	10	35	41	35		35		156
Sheep urine		34	42	46		62		184
Sheep dung		40	31	15		44		130
Total	40	398	170	199	70	330	10	1217

Key: North = Northland, Wai = Waikato, HB = Hawkes Bay, Man = Manawatu, Cant = Canterbury, South = Southland.

Table 4 Mean and range of excreta N loads (kg N/ha) in the dataset for each livestock type and excreta type.

N source	Mean	Minimum	Maximum
Dairy cattle urine	717	367	1130
Dairy cattle dung	1002	574	1390
Non-dairy cattle urine	340	207	589
Non-dairy cattle dung	847	481	1217
Sheep urine	231	47	504
Sheep dung	293	191	449

Table 5 Pooled emission factors (%, mean and 95% confidence interval (CI)) calculated for excreta type, livestock type and topography where values were not significantly different.

Livestock type	Excreta type		Topography	
			Flatland & Low slope (< 12°)	Medium & Steep slopes (> 12°)
All livestock	Dung	Mean	0.12	
		95% CI	0.11-0.15	
Cattle (dairy + non-dairy)	Urine	Mean	0.98	0.33
		95% CI	0.87-1.09	0.23-0.42
Sheep	Urine	Mean	0.50	0.08
		95% CI	0.34-0.67	0.05-0.11
Deer[#]	Urine	Mean	0.74	0.20
		95% CI	n/a*	n/a

[#] N_2O emissions have not been measured for deer urine. Deer EF_3 values were estimated as the average of EF_3 values for cattle and sheep based on the following rationale: i) Cattle and sheep urinate, on average, 1.7 and 0.15 L per urination event respectively, while average N concentrations are similar (between 7 and 9 g N/L) (Haynes and Williams 1993; Selbie et al. 2015). On this basis, we propose that the difference in EF_3 for sheep and cattle was due to differences in urine volume per event; ii) No data exist for deer urine volumes. But given urine volume is generally related to body size (i.e. the larger the body, the larger the bladder), and the average liveweights for sheep, deer and non-dairy cattle New Zealand are 52, 127 and 552 kg, respectively (IPCC, 2017), we have assumed the volume of urination events from deer will lie between that of cattle and sheep. * n/a, not applicable.

Credit author statement

T.J. van der Weerden: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation; Methodology, Project administration, Visualization Writing - original draft, Writing - review & editing

A.N. Noble: Formal analysis; Methodology; Writing - original draft; Writing - review & editing

J. Luo: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing - original draft, Writing - review & editing

C.A.M. de Klein: Writing - review & editing

S. Saggar: Conceptualization, Funding acquisition, Methodology, Writing - original draft, Writing - review & editing

D. Giltrap: Conceptualization, Data curation, Funding acquisition, Methodology, Writing - original draft; Writing - review & editing

J. Gibbs: Conceptualization, Data curation, Writing - review & editing

G. Rys: Conceptualization, Writing - review & editing

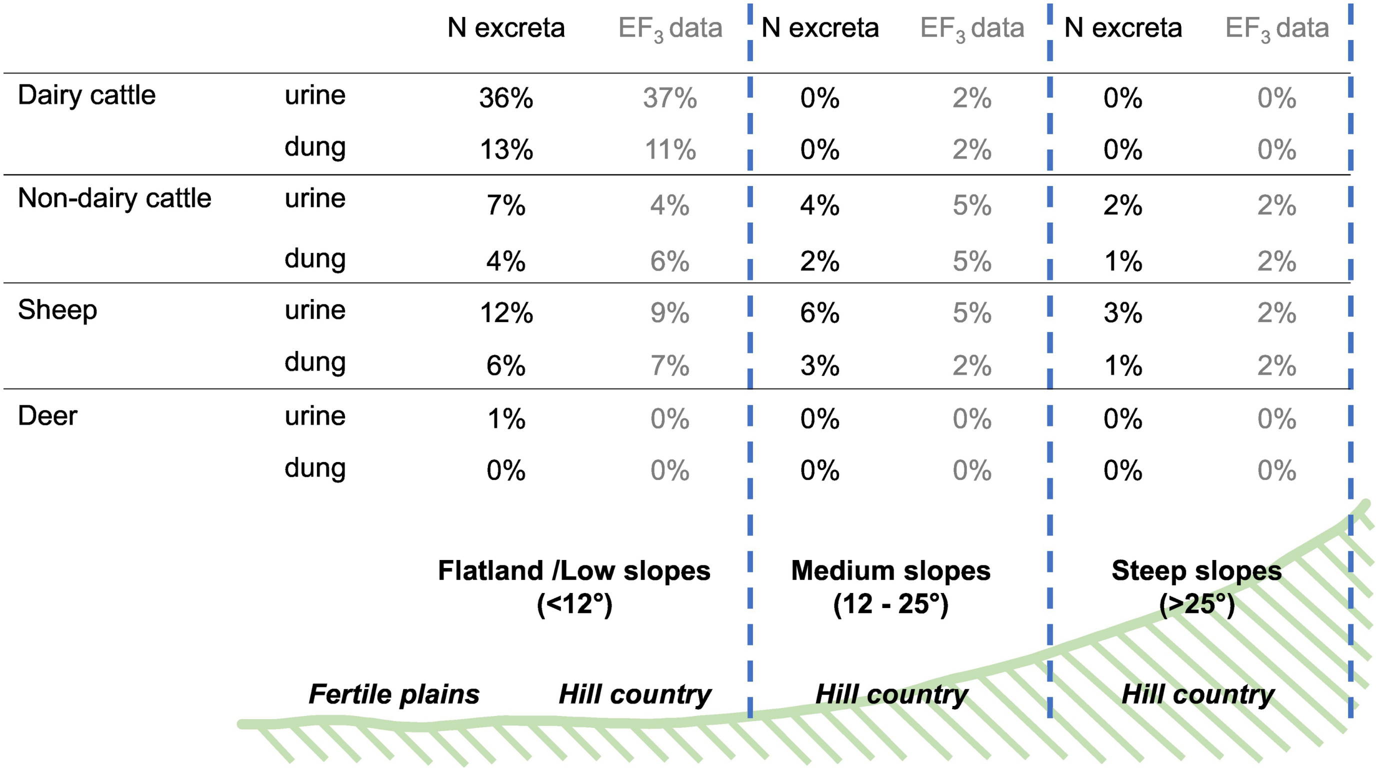
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Graphical abstract

Highlights

- Current NZ-specific N_2O emission factors (EF_3) are 1.0% (urine) and 0.25% (dung)
- A meta-analysis of 1217 EF_3 data representative of livestock grazing was completed
- The analysis showed that the dung EF_3 values should be reduced to 0.12%
- Urine EF_3 values ranged from 0.08% to 0.98%, based on livestock type and topography
- We recommend the revised values are employed in NZ's national N_2O inventory



		Flatland /Low slopes (<12°)		Medium slopes (12 - 25°)		Steep slopes (>25°)	
		N excreta	EF_3 data	N excreta	EF_3 data	N excreta	EF_3 data
Dairy cattle	urine	36%	37%	0%	2%	0%	0%
	dung	13%	11%	0%	2%	0%	0%
Non-dairy cattle	urine	7%	4%	4%	5%	2%	2%
	dung	4%	6%	2%	5%	1%	2%
Sheep	urine	12%	9%	6%	5%	3%	2%
	dung	6%	7%	3%	2%	1%	2%
Deer	urine	1%	0%	0%	0%	0%	0%
	dung	0%	0%	0%	0%	0%	0%

Figure 1

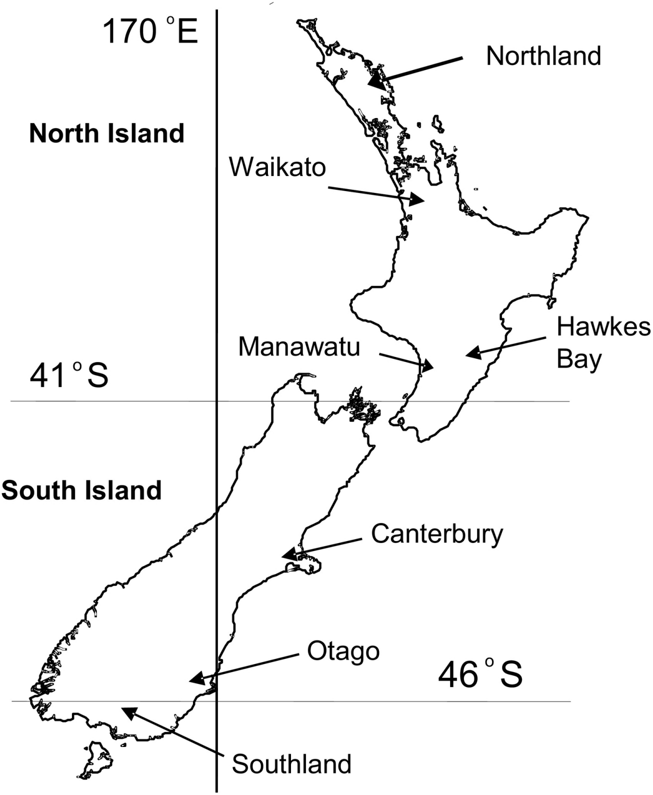

170 °E
Northland
North Island
Waikato
Manawatu
Hawkes Bay
41 ° S
South Island
Canterbury
Otago
46 ° S
Southland

Figure 2

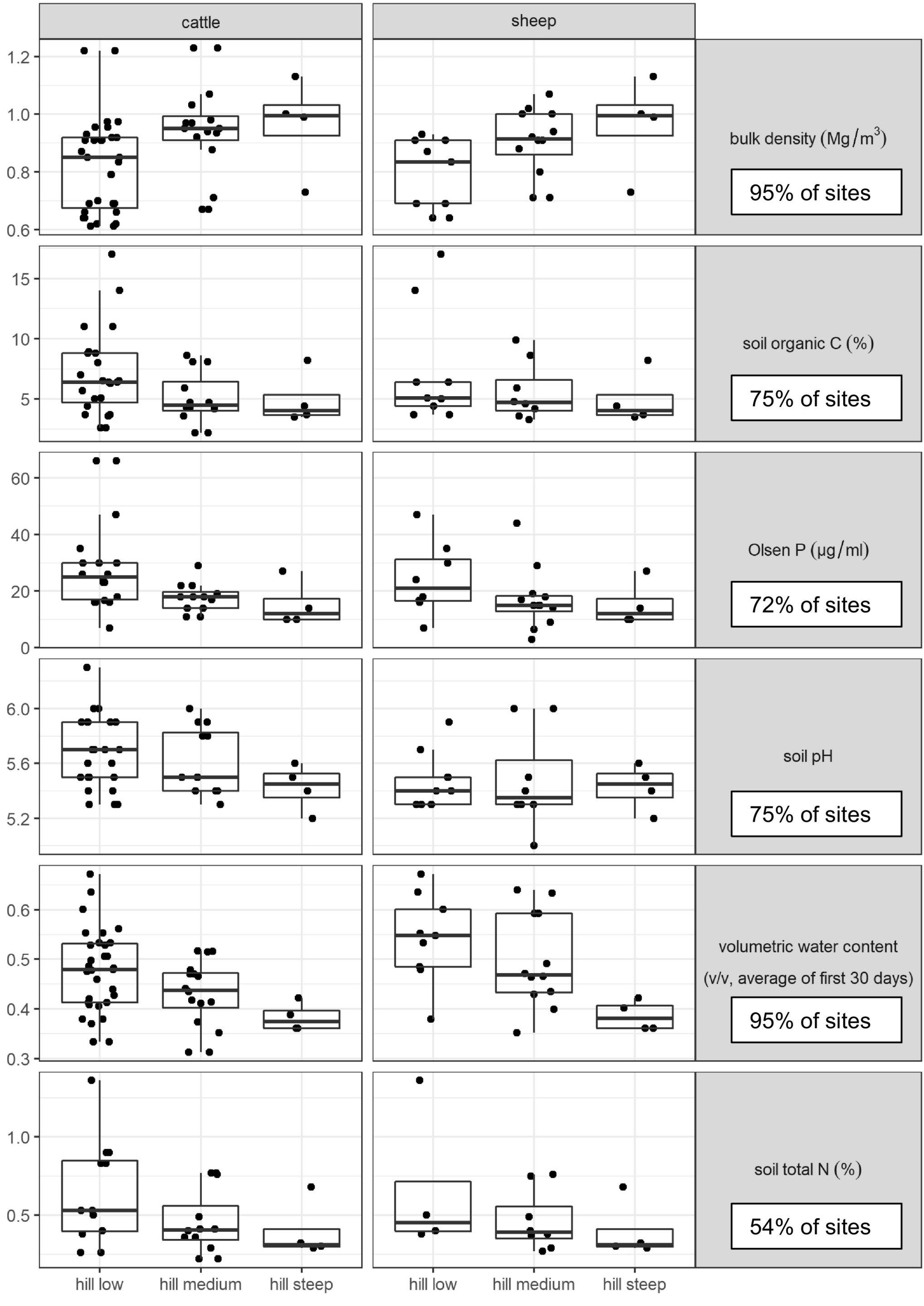

cattle
sheep
bulk density (Mg/m^3)
95% of sites
soil organic C (%)
75% of sites
Olsen P (µg/ml)
72% of sites
soil pH
75% of sites
volumetric water content
(v/v, average of first 30 days)
95% of sites
soil total N (%)
54% of sites
1.2
1.0
0.8
0.6
15
10
5
60
40
20
0
6.0
5.6
5.2
0.6
0.5
0.4
0.3
1.0
0.5
hill low
hill medium
hill steep
hill low
hill medium
hill steep

Figure 3

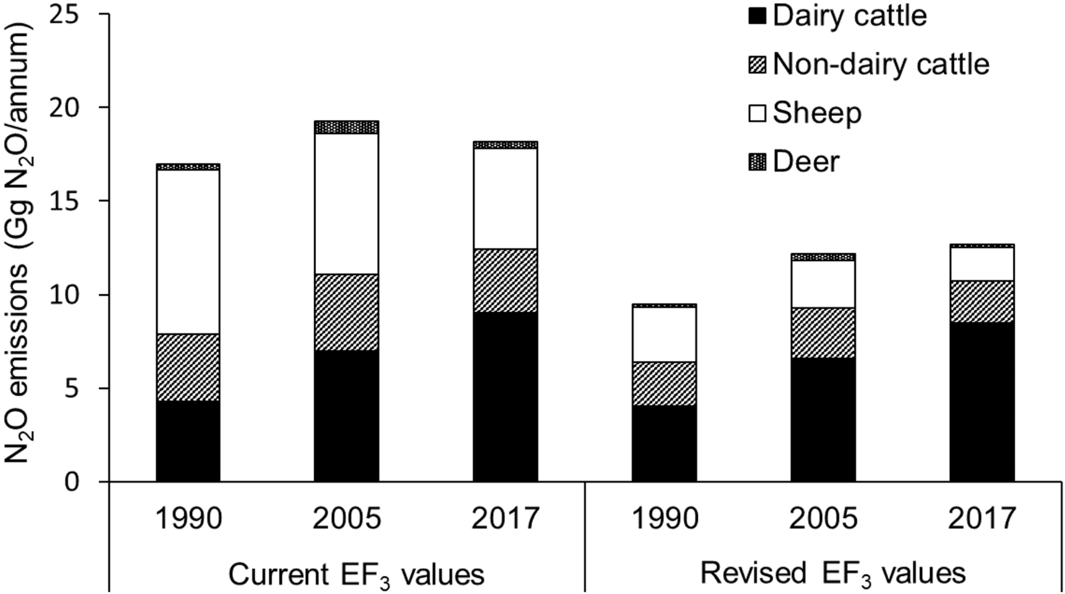

N₂O emissions (Gg N₂O/annum)
25
20
15
10
5
0
Dairy cattle
Non-dairy cattle
Sheep
Deer
1990
2005
2017
1990
2005
2017
Current EF₃ values
Revised EF₃ values

Figure 4

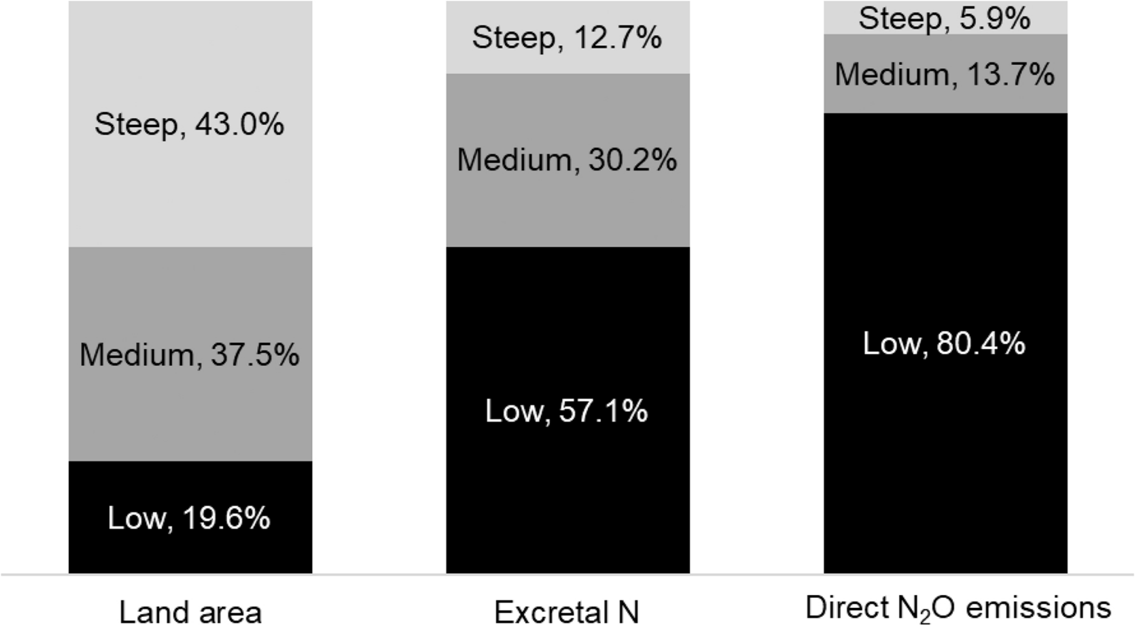

Steep, 43.0%
Medium, 37.5%
Low, 19.6%
Steep, 12.7%
Medium, 30.2%
Low, 57.1%
Steep, 5.9%
Medium, 13.7%
Low, 80.4%
Land area
Excretal N
Direct N_2O emissions

Figure 5