Meta-analysis of nitrous oxide emission factors for excreta deposited onto pasture: final report

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1. Executive Summary

The Ministry for Primary Industries (MPI) plan to update the national N_2O inventory for nitrous oxide (N_2O) emissions from dung and urine deposited onto pasture. This includes disaggregation of dung and urine emission factors (EF_{3PRP}; representing the percentage of N deposited being lost as N_2O, hereafter termed EF_3) into the four main livestock classes: dairy cattle, non-dairy cattle, sheep and deer. An earlier meta-analysis showed that EF_3 values for animal urine and dung deposited on medium (12 - 24°) slopes were significantly lower than those from low (0 - 12°) slopes (Kelliher et al. 2014). Since that earlier analysis, additional flatland and hill country field studies have been conducted, including studies on hill country steep slopes, to determine dung and urine EF_3. 'Flatland' is defined as large areas of flat pastoral land, typically represented as plains, where the slope is typically <12°. 'Hill country' represents hill and high country pastoral land, separated into three slope classes: low (0 - 12°), medium (12 - 24°) and steep (> 24°) slopes.

The **objectives** of this study were to update the EF_3 database and conduct a meta-analysis to determine the most suitable EF_3 values for dairy cattle, non-dairy cattle, sheep and deer grazing flatland and low (0 - 12°), medium (12 - 24°) and steep (> 24°) slopes in hill country.

A four-step procedure was adopted for this study:-

- Step 1: conduct a meta-analysis of the updated EF_3 database ('methods'). The available data is limited to dairy cattle, non-dairy cattle and sheep, therefore values for deer would be derived from this analysis,
- Step 2: derivation of two sets of EF_3 values ('scenarios') for dairy cattle, non-dairy cattle, sheep and deer based on the analysis in Step 1, where set 1 was based on individual (non-pooled) EF_3 values and set 2 was based on pooled EF_3 values.
- Step 3: estimate total N_2O emissions from excreta deposition onto pasture for 1990, 2005 and 2017 for each of the EF_3 'scenarios'.
- Step 4: recommend EF_3 values for dairy cattle, non-dairy cattle, sheep and deer on flatland and hill country to be used in the national N_2O inventory.

In **Step 1** we compared two different methods for determining EF_3 values from the updated database. We identified 21 different livestock class (dairy cattle, non-dairy cattle and sheep) x excreta type (dung and urine) x topography (flatland, low slope, medium slope and steep slope) combinations in the updated database, with all combinations included apart from beef dung on flatland and dairy catle urine and dung on steep slopes. The methods used were:-

- Method 1: arithmetic means of available data for each of the 21 combinations,
- Method 2: arithmetic means pooled where values were not significantly different, resulting in five unique EF_3 values

The results from Step 1 were used in **Step 2** to derive two sets of EF_{3PRP} values (called 'scenarios') for dairy cattle, non-dairy cattle, sheep and deer, where deer values were estimated by averaging data from non-dairy cattle and sheep, given the average liveweights of these livestock classes.

Step 3 showed that when each scenario is combined with N excreta data, calculated total N_2O emissions from dairy cattle, non-dairy cattle, sheep and deer in 2017 were reduced by *ca* 70% compared to using the current EF_{3PRP} values of 1% and 0.25% for urine and dung, respectively. The impact of using individual EF_{3PRP} values compared to five pooled EF_{3PRP} values was relatively small (< 100 kt CO_2 equivalent per year).

Our **recommendation** (**Step 4**) is that updated EF_{3PRP} values for estimating N_2O emissions from excreta deposited onto pasture should be based on the pooled values. This provides a statistically-based approach to the calculation of EF_3 values, and aligns with previous meta-analysis studies (e.g. Kelliher et al. 2014).

The current and recommended EF_{3PRP} values (%) to be adopted within the national GHG inventory are shown below:

Livestock type	**Excreta type**	**Topography**	
		Flatland & Low slope (< 12°)	Medium & Steep slope (> 12°)
Current values			
All livestock	Dung	0.25	
All livestock	Urine	1.00	
Recommended values			
All livestock	Dung	0.12	
Dairy* & non-dairy cattle	Urine	0.98	0.33
Deer	Urine	0.74	0.20
Sheep	Urine	0.50	0.08

* it is assumed all dairy excreta is deposited on to Flatland

2. Background

Urine and dung deposition during livestock grazing is the primary source of nitrous oxide (N_2O) emissions in New Zealand, contributing 5,414 kt carbon dioxide equivalents (CO_2-e) to the total greenhouse gas (GHG) emissions in 2017 (Ministry for the Environment 2019). This represents 76% of direct N_2O emissions from agricultural soils and 14% of emissions from the agricultural sector. Nitrous oxide emissions from urine and dung deposited onto soil have increased 7% over 27 years in New Zealand since 1990. This is primarily due to the dairy cattle population increasing by 90% over the same period, while sheep, non-dairy cattle and deer numbers have reduced by 53%, 21% and 14%, respectively (Ministry for the Environment 2019). New Zealand's N_2O emissions from grazing livestock have been calculated using the country specific emission factors (EF_{3PRP}; representing the percentage of N deposited being lost as N_2O, hereafter termed EF_3) of 1% and 0.25% for urine and dung, respectively. These values are applied to excreta deposited by dairy cattle, non-dairy cattle, sheep and deer.

In grazed hill country, however, slope influences soil characteristics, pasture production, pasture N content and intake, excreta deposition and environmental conditions such as soil bulk density, moisture and fertility (Saggar et al. 1990; MacKay et al. 1995; Luo et al. 2018, 2019). Over the past 10 years, a series of field studies (de Klein et al. 2009; Hoogendoorn et al. 2013; Luo et al. 2013, 2016a, 2019; Saggar et al. 2015) have demonstrated that N_2O emissions and EF_3 values for sheep, non-dairy- and dairy-cattle excreta are generally lower on steeper slopes than on lower slopes or flatland. Indeed, an earlier meta-analysis confirmed that EF_{3PRP} values for animal urine and dung deposited on medium (12 - 24°) slopes were significantly lower than those from low (0 - 12°) slopes (Kelliher et al. 2014). Since that earlier analysis, additional flatland and hill country field studies have been conducted, including studies on hill country steep slopes, to determine dung and urine EF_3.

Disaggregation of EF_3 for urine and dung deposited by different livestock classes (non-dairy cattle, sheep and deer) onto different hill country slope classes would provide a more accurate inventory of national N_2O emissions. Saggar et al. (2015) proposed a revision to the inventory structure that would account for the effect of land slope on the N_2O emissions from livestock grazing hill country. Since then MPI (Ministry for Primary Industries) have made the necessary changes to the agricultural GHG inventory architecture to incorporate the recommended changes to the inventory structure. Before the revised calculation of N_2O emissions from dung and urine can be implemented, MPI require recommendations on which EF_3 values to employ for non-dairy cattle, sheep and deer grazing hill country. Given the additional studies on N_2O emissions from dairy cattle grazing since the review by Kelliher et al. (2014), we also revised the EF_3 values for this livestock class grazing flatland.

3. Project Objectives

The objectives of this study were to update the New Zealand EF_3 database and conduct a meta-analysis to determine the most suitable EF_3 values for dairy cattle, non-dairy cattle, sheep and deer grazing pastures.

4. Methods

A four-step process was adopted for this study (Fig. 1):-

- Step 1: a meta-analysis of the updated EF_3 database ('methods'). The available data is limited to dairy cattle, non-dairy cattle and sheep, therefore values for deer would be derived from this analysis,
- Step 2: derivation of two sets of EF_3 values ('scenarios') for dairy cattle, non-dairy cattle, sheep and deer based on the analysis in Step 1, where set 1 was based on individual (non-pooled) EF_3 values and set 2 was based on pooled EF_3 values.
- Step 3: estimate total N_2O emissions from excreta deposition onto pasture for 1990, 2005 and 2017 for each of the EF_3 'scenarios'.
- Step 4: recommend EF_3 values for dairy cattle, non-dairy cattle, sheep and deer on flatland and hill country to be used in the national N_2O inventory.

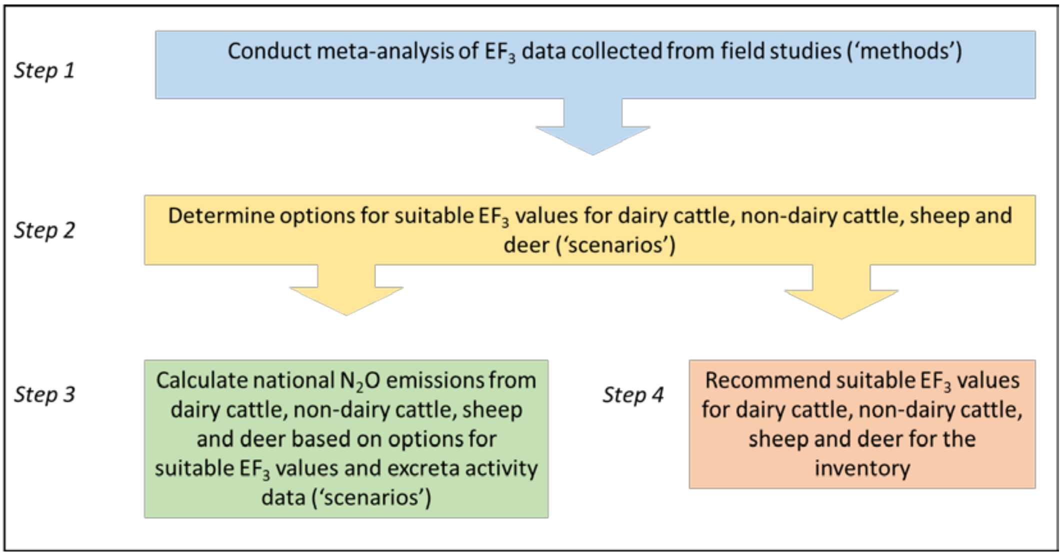

Figure 1: Schematic of procedure adopted for the meta-analysis of EF_3 data and derivation of recommended values for use in the national N_2O inventory.

4.1 Data collation and description

The original meta-analysis N_2O emission factors (EFs), conducted by Kelliher et al. (2014), included collation and analysis of a database of N_2O emission factors for dung and urine deposited onto pastoral land (EF_3) and fertiliser applied to pastoral land (EF_1) in New Zealand. The original database was limited to flatland sites and hill country sites on low and medium slope only, with no data available for steep slopes. Since that earlier analysis, additional flatland and hill country EF_3 field studies have been conducted, including studies on hill country steep slopes.

Following the approach of Kelliher et al. (2014), the EF database was expanded for the current analysis. For this EF_3-specific 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 was excluded (van der Weerden et al. 2016).

Data was collated at the replicate level and included the cumulative N_2O loss (kg N_2O-N/ha) from the N source (dung or urine), an associated control (nil N and nil water applied) and the N load (kg N/ha). For example, collating data from a field trial where each treatment was replicated 5 times would result in 5 separate cumulative losses for a specific treatment in the database. From this, we calculated the excreta emission factor (EF_3) at each replicate level:-

$$EF_3 = \frac{\text{Excreta N}_2\text{O} - \text{Control N}_2\text{O}}{\text{N load}} \times 100\%$$

where EF_3 is the emission factor (N_2O-N emitted as a % of N applied) for urine or dung. Excreta N_2O is the cumulative N_2O emission from urine or dung (kg N_2O-N/ha), Control N_2O is the cumulative N_2O emission from the control plots (kg N_2O-N /ha) and N load is the rate of N applied as urine or dung (kg N/ha).

In total, we collated 1217 replicate-level EF_3 values, with urine and dung EF_3 values totalling 781 and 436 values, respectively (Table 1). The field campaigns that generated these data were conducted from 2000 to 2017 across a range of slopes, during different seasons, in different regions across New Zealand, and on soils with varying drainage classes. These studies have either been published in scientific journals (Cameron et al. 2014; de Klein et al. 2003, 2011, 2014; Hoogendoorn et al. 2008, 2016a; Ledgard et al. 2014; Luo et al. 2008, 2013, 2015, 2019; van der Weerden et al. 2011) or have been reported directly to MPI as client reports (de Klein et al. 2004; Hoogendoorn et al. 2013; Luo et al. 2009, 2010, 2016, Sherlock et al. 2003a, 2003b).

An examination of the dataset showed that it was imbalanced (Table 1). For example, the distribution of EF_3 values across the topographies showed that flatland had the largest total number of datapoints (516). On hill country terrain, low slope data dominated the dataset, at 382, followed by medium and steep slopes, at 240 and 80 EF_{3PRP} values, respectively. Furthermore, there were no dairy cattle excreta data for steep slopes, nor any non-dairy cattle dung data for flatland. There was only 1 study measuring non-dairy cattle urine emission factors from flatland (Table 1). For statistical analysis, data was log transformed due to its non-normal distribution (Fig. 2).

Table 1: Number of replicate-level EF_3 values for each N source and topography class. Number of individual trials shown in brackets

N source	Flatland	H/C[A] - low slope	H/C - medium slope	H/C - steep slope	Total
Dairy cattle urine	341 (57)	108 (22)	20 (4)		469 (83)
Dairy cattle dung	84 (19)	46 (9)	20 (4)		150 (32)
Non-dairy cattle urine	8 (1)	40 (8)	60 (12)	20 (4)	128 (25)
Non-dairy cattle dung		76 (16)	60 (12)	20 (4)	156 (32)
Sheep urine	40 (7)	64 (12)	60 (12)	20 (4)	184 (35)
Sheep dung	54 (13)	36 (8)	20 (4)	20 (4)	130 (29)
Total Urine	389 (65)	212 (42)	140 (28)	40 (8)	781 (143)
Total Dung	138 (32)	158 (33)	100 (20)	40 (8)	436 (93)
Total Excreta	527 (97)	370 (75)	240 (48)	80 (16)	1217 (236)

[A] H/C = Hill Country

The distribution of EF_3 values across the topography classes and seasons is shown in Table 2. Season for each trial was defined by determining which month the trial's 15th day occurred as follows: January, February and December for summer, March, April and May for autumn, June, July and August for winter and September, October and November for spring, as previously used by Kelliher et al. (2014). At a seasonal level, winter represented the largest number of EF_3 values (448, or 37% of the dataset), covering the greatest range of N sources (livestock type and excreta type). Autumn was the next well represented season, followed by spring. The least represented season was summer, with 132 EF_3 values representing only 11% of the total dataset, with data limited to low slopes apart from 12 replicate-level EF_3 values for dairy cattle urine on flatland and 40 replicate-level EF_3 values for non-dairy cattle excreta on medium slopes. There are no sheep excreta EF_3 data for summer.

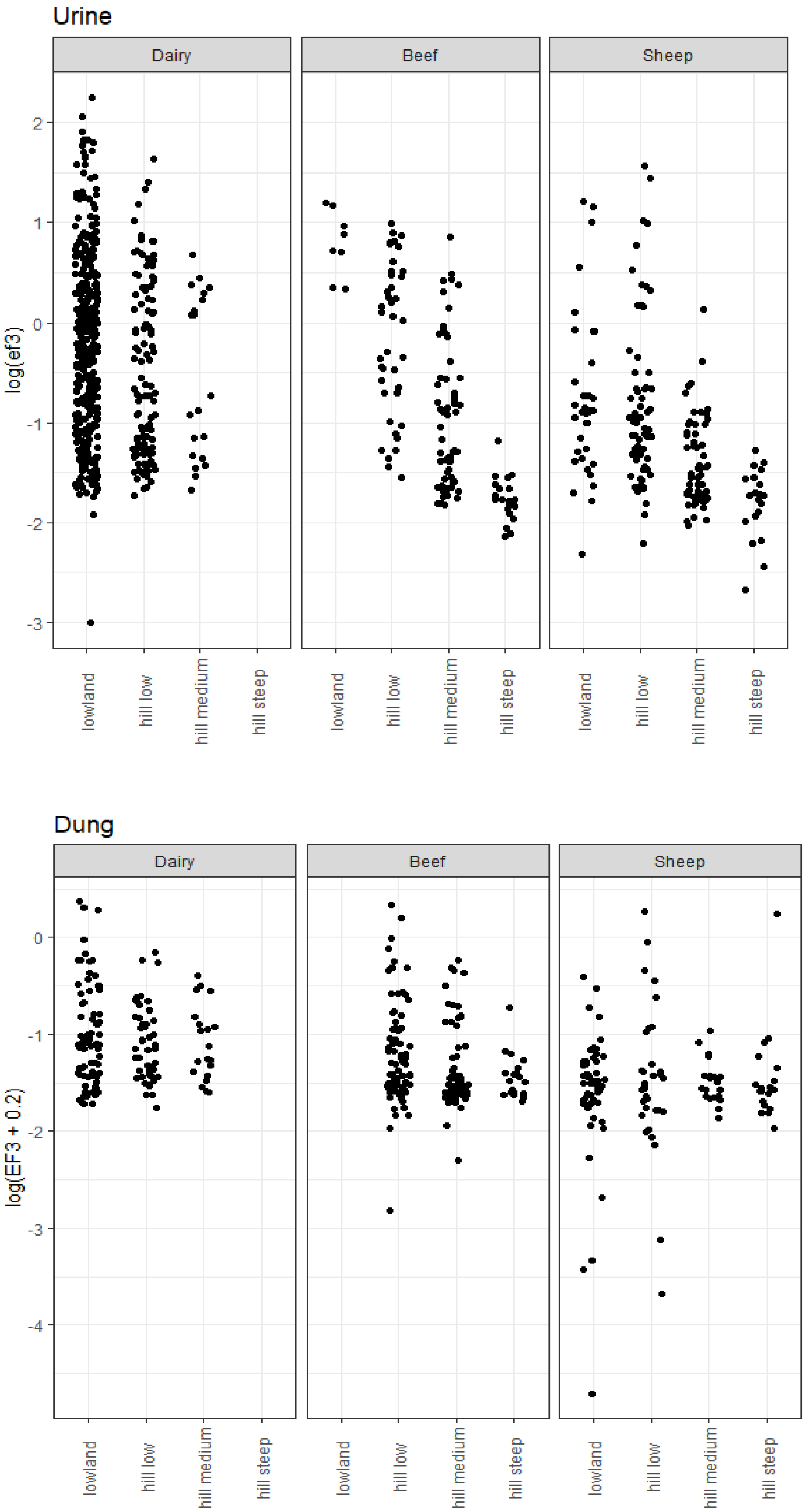

Figure 2: Distribution of log transformed urine EF_3 (top) and dung EF_3 (bottom) values for dairy cattle, non-dairy cattle and sheep on flatland and hill country low, medium and steep slopes.

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		358	447	280	132	1217

The field studies were conducted in seven regions across New Zealand, from Northland in the north to Southland in the south (Table 3). Waikato has had the largest number of field campaigns, with nearly 400 values coming from this region. In contrast, only 10 values were derived from Southland. For each field campaign, considerable thought was given to the location to ensure they were representative of the livestock class being studied.

Table 3 Distribution of flatland and hill country EF_3 values by regional authority.

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.

Field campaigns were well distributed across freely and poorly drained soils, with several campaigns conducted on imperfectly drained soils (Table 4).

Table 4 Distribution of flatland and hill country EF_3 values by soil drainage class.

N source	Freely drained	Imperfectly drained	Poorly drained
Dairy cattle urine	215	34	220
Dairy cattle dung	81	14	55
Non-dairy cattle urine	90		38
Non-dairy cattle dung	113		43
Sheep urine	98		86
Sheep dung	73		57
Total	670	48	499

4.2 Statistical analysis of emission factors

Two models were fitted to the data; one with a log transformation of the data and a Gaussian linear model and the other with a generalized linear model fitted to the raw data with a Poisson distribution and logarithmic link. Both models have assumptions that are not completely met however they give consistent conclusions. The log transformation of the data incurs issues as there are negative and zero values in the dataset. Thus an offset, equal to the minimum value plus a small amount, was added to all of the data values. A generalized linear mixed model with a Gaussian distribution was then fitted to these transformed values, with excreta type (urine vs dung), livestock type (dairy cattle vs non-dairy cattle vs sheep), topography (flatland, low slope, medium slope and steep slope) as fixed effects and site as a random effect. Excreta type was included because the form of excreta-N in urine and dung differs, which affects the magnitude of EF_3, as noted erlier. Livestock type was included as this can influence the amount of dung and urine voided per excretion event, in addition to sheep having a generally lower impact on soil compaction due to their lower body liveweight.

The Poisson model also required the same transformation to eliminate negative, and zero, values but the response variable was modelled on the raw scale with a logarithmic link function. The same fixed and random effects included in the Gaussian model were included here. The Poisson model assumes that the mean and variance are linearly related. Residual analysis of the two models showed minor shortcomings in both.

Results from the two models were similar, although not identical, in all analyses. Sometimes groupings varied a little but the general message was consistent between the two models. These models were used to identify differences in the groupings of animal types and topographies for dung and urine. These were used to finalise the groupings for the estimates of emission factors. The final estimates of the emission factors were arithmetic means of the data for each of the identified groups.

4.2.1 Assessment of data suitability

The dataset included EF_3 data generated from plot (n=1174) and lysimeter (n=44) studies and, for urine EF_3, data generated using real (n=346) and synthetic (n=24) urine. To determine whether EF_3 values were influenced by the method of field study or the use of synthetic urine as an alternative to real urine, the data were graphed and, where deemed necessary, analysed by testing the effect using the models described in 4.2.

Lysimeter data

The lysimeter data was restricted to flatland studies and included both dairy cattle dung and urine N sources. The EF_3 values from the 44 lysimeter studies were evenly distributed amongst the plot-based field studies (Fig. 3). Therefore, we retained the lysimeter-derived data for the meta analysis. Also shown in Fig. 3 is a single large negative dung EF_3 value; this value has been retained as there was no justifiable reason for excluding it.

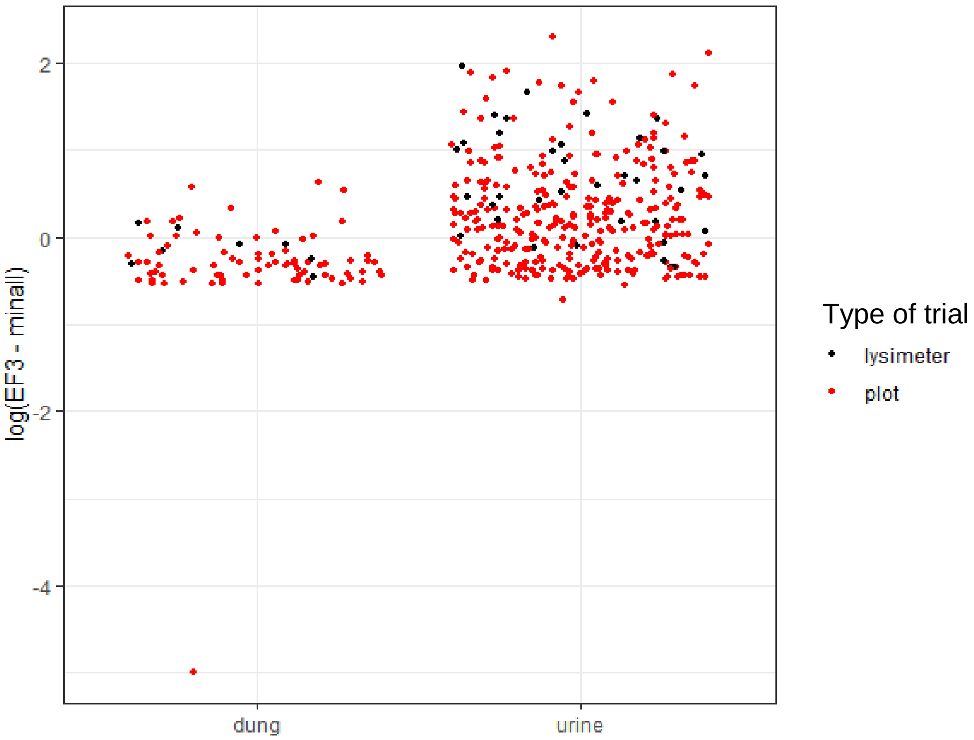

Figure 3: Flatland EF_3 data (presented on a log basis) for dung and urine determined from either plot (red symbols) or lysimeter studies (black symbols).

Synthetic urine

Results showed that the synthetic urine EF_3 data from flatland studies are evenly dispersed throughout the dataset generated from real urine (Fig. 4). However, the results from synthetic urine applied to low slopes appear to be at the upper end of the range of urine EF_3 values obtained using real urine collected from dairy cattle and sheep (Fig. 2). These low slopes data were generated from a field experiment conducted in Otago (de Klein et al. 2003) where synthetic urine was used to represent dairy cattle and sheep N loads. The same study included real dairy urine, which also produced relatively high EF_3 values. The authors found no significant difference between the EF_3 values determined from real and synthetic dairy cattle urine ($P > 0.05$). Our analysis of the entire low slope urine dataset for dairy cattle and sheep showed synthetic urine had no significant effect on EF_3 ($P > 0.05$). On this basis we have retained all synthetic urine EF_3 data for the meta analysis.

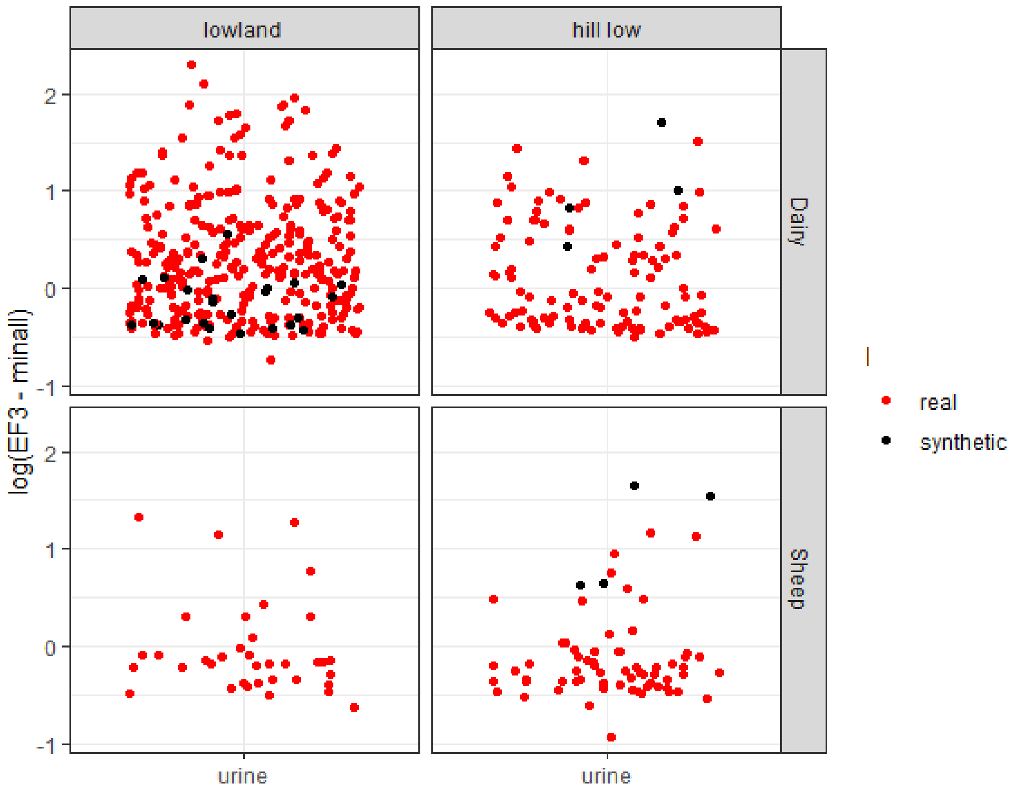

Figure 4: Flatland EF_3 urine data (presented on a log basis), generated using either real (red symbols) or synthetic urine (black symbols), when measured from flatland or hill country low slopes.

4.2.2 Assessment of excreta N load effect

A wide range of nitrogen (N) loads were employed in the field experiments. While field experiments apply urine or dung in terms of g N/m^2, N loads are presented on a 'kg N/ha' equivalence basis (Table 5). It is unclear whether the N load has a positive, neutral or negative effect on EF_3 (de Klein et al. 2019). Therefore, we analysed the dataset to explore any possible 'N load effect', given a positive or negative effect on EF_3 would most likely require excreta N load to be included in the national inventory methodology for estimating N_2O emissions from livestock grazing. The N load was included in the models described earlier as a covariate and its effect assessed in the model.

Results showed that there was no N load effect on EF_3 when all data were pooled ($P = 0.85$). This non-significant effect of N load was generally maintained when data were separated into livestock class (dairy cattle, non-dairy cattle and sheep) and excreta type (urine and dung), apart from beef urine (Fig. 5). 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 studies was limited to between 207 and 589 kg N/ha. Given the non-significant N load effect observed for dairy urine, where a wider range of N loads were used in field studies (ranging from 367 to 1130 kg N/ha), and the absence of beef urine studies on flatland, we suggest that further experimentation using a wider range of N loads and inclusion of flatland sites is required to confirm whether an N load effect exists for this N source. On the basis of no N load effect on EF_3 across the pooled data, data analysis proceeded without including the effect of N load.

Table 5 Mean and range of excreta N loads (kg N/ha) in 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

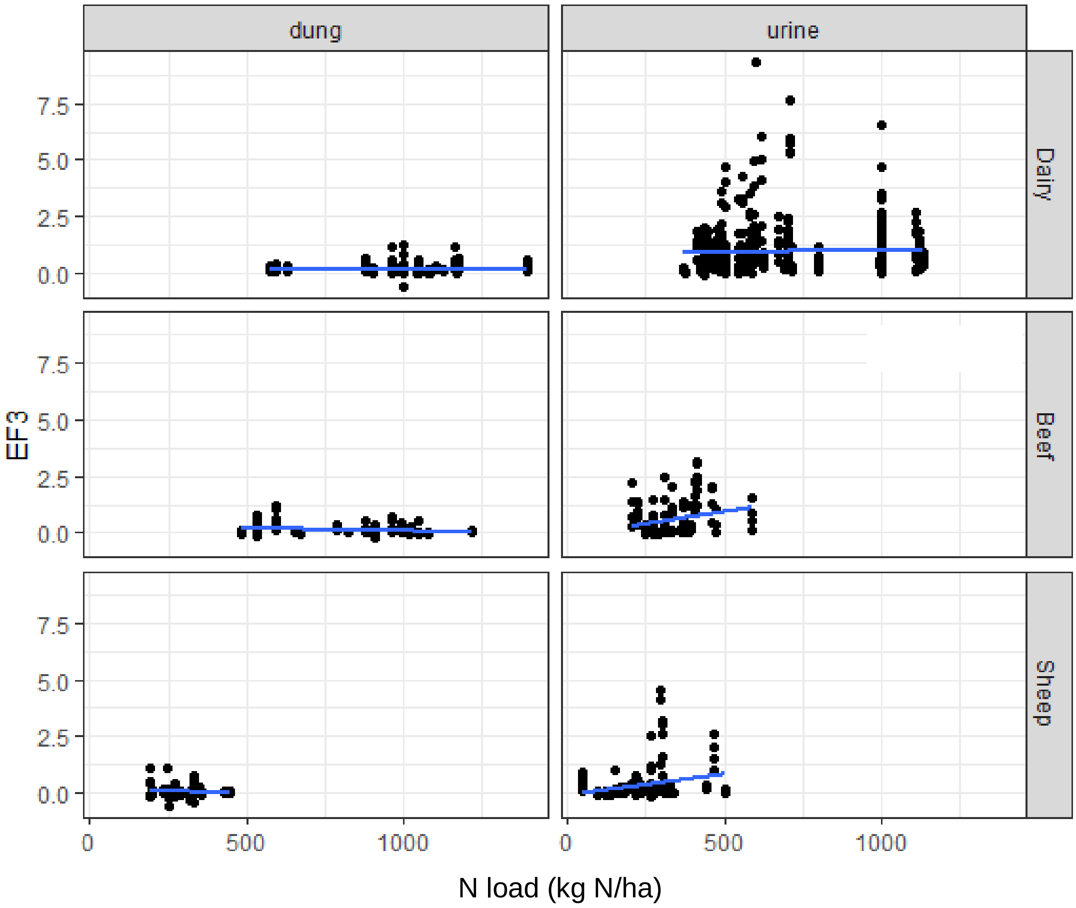

Figure 5: Influence of N load (kg N/ha) on EF_3 (%) for different livestock classes and excreta types. The fitted blue line represents the linear relationship between N load and EF_3 for each combination.

4.2.3 Determining EF_3 values for the inventory methodology

The aim of the data analysis was to generate EF_3 values for a total of 21 different livestock x excreta type x topography class combinations. An initial generalised linear mixed model was fitted to the entire data set including a random term for the sites. This random term explained little of the variability so simpler models were investigated as they are more easily interpreted. The final model used for the analysis was based on the average EF_3 per treatment, weighted by the number of replicates in each trial.

We adopted two methods for determining emission factors for hill country:

- Method 1: arithmetic means of available data for each of the 21 combinations,
- Method 2: arithmetic means pooled where values were not significantly different.

A description and justification for each method employed is provided below.

Method 1: means of available data for each of the 21 combinations

This approach ensured a unique emission factor was provided for each of the 21 combinations. By maintaining all livestock class x excreta type x slope class combinations, EF_3 values for a given combination can be updated based on new research independently of other combinations that may not have been included in that research. A further advantage of this method is greater transparency in the extent of N_2O emissions from different livestock and slope classes.

Method 2: means pooled where values are not significantly different

By analyzing the data for differences between excreta type, livestock classes and slope classes, EF_3 values can be pooled where no significant differences exist. This provides a statistically-based approach to the calculation of EF_3 values, and aligns with previous meta-analysis studies (e.g. Kelliher et al. 2014).

4.3 Nitrous oxide emissions from excreta deposition in New Zealand

National N_2O emissions from excreta deposition were calculated for both methods using the emission factors for dairy cattle, non-dairy cattle and sheep found in Tables 5 and 6. For deer we used the average of the sheep and non-dairy cattle EFs. As deer excreta only accounts for 2-3% of the national N excreta, this assumption should have little impact on the total N_2O emission.

The total amount of dung and urine N excreted by year and animal species was taken from the national agricultural inventory model (data provided by MPI).

For dairy cattle it was assumed that all the excreta was deposited on to flatland. For sheep, non-dairy cattle, and deer we used survey data from Beef + Lamb New Zealand that divided animal numbers across 17 different farm classes with similar geography and management. The proportion of low, medium and steep slope land 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.

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), and the nutrient transfer model take into account animal behaviour with relatively more time spent on the lower slopes.

5. Results and Discussion

5.1 Emission factors from meta-analysis

Below we describe and discuss the results of the two different methods for calculating EF_3 values (Figures 6 and 7). Tabulated values are provided in Appendix 1.

Method 1: means of available data for each of the 21 combination.
EF_3 values for all 21 combinations of excreta based on the arithmetic means are shown in Figure 6. See Table A1-1 for tabulated values. EF_3 values were generally the highest for flatland, followed by hill country low slopes, medium slopes and then steep slopes. While sheep dung had a higher EF_3 value on the steep slope than on the medium slope, there was no significant difference between the values ($P > 0.05$).

Non-dairy cattle urine had a high EF_3 value of 2.14%, more than double the value of dairy cattle urine (1.04%) on the same class of land. However, the data supporting the high non-dairy cattle urine value was sourced from a single study conducted in winter under relatively wet conditions (*ca* 80% water filled pore space during first 6 weeks) (Hoogendoorn et al. 2016a). These conditions are conducive to producing relatively high EF_3 values (van der Weerden et al. 2014). Given the conditions of this single study do not reflect average or even near average conditions, we suggest the resulting EF_3 value for non-dairy cattle urine on flatland is not representative. This demonstrates the imbalanced nature of the dataset.

The data show that sheep urine produced lower EF_3 values than cattle urine for flatland, and hill country low and medium slopes. However, on steep slopes, sheep and cattle urine

EF_3 values were similar albeit both very low (Fig. 6). Urine was applied at a urine volume per patch area of 4 L/m^2 and 10 L/m^2, for sheep and cattle, respectively (Luo et al. 2013). The difference in urine volume:surface area is likely to influence the uptake of urine N by pasture. At the same urine N concentration sheep urine is expected to result in more N uptake compared with cattle urine. Given this assumed increase in N uptake efficiency from sheep urine patches, it is not surprising that sheep urine EF_3 values were lower than those for cattle urine for the low and medium slopes. Sheep urine EF_3 was found to be significantly lower than cattle urine EF_3 in the original meta-analysis (Kelliher et al. 2014).

It was evident that slope has a larger influence on urine EF_3 than on dung EF_3, with the relative differences in EF_3 values being greater for the former. The effect of slope on urine EF_3 is thought to be due to a combination of lower soil microbial activity and soil fertility (Luo et al. 2013). For instance, soil C:N ratio was found to be significantly greater on steep slopes compared lowers slopes on the Ballantrae sheep hill country station (Hoogendoorn et al. 2016b). Under such conditions, greater immobilization of urine-N can be expected. In a parallel study at the same farm, Zhong et al. (2016) observed higher nitrification and denitrification activity in low sloping soils compared to medium and steep sloping soils. These workers also found that the low sloping soils had a greater abundance of key functional microbial groups responsible for nitrification and denitrification, compared to steper slopes. This farm has been used for several N_2O field experiments (e.g. Luo et al. 2013, 2016). .

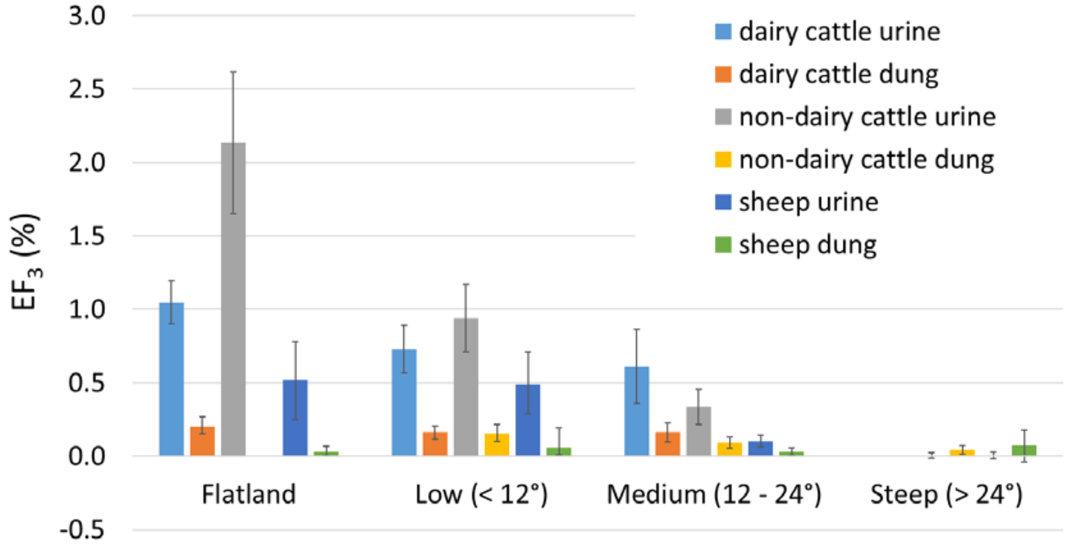

Figure 6: Emission factors (%) calculated using non-pooled means (Method 1). Error bars represent 95% confidence interval.

Method 2: means pooled where values are not significantly different

Statistical analysis of the database, conducted on log-transformed data, using a Tukey multiple comparison of means produced the following key results. For each comparions of variables, we examined the results based on both a gaussian distribution and a poisson distribution. Pairwise comparisons at the 5% level are given using letter-based representations.

Excreta type.

Urine EF_3 values were significantly greater than dung EF_3 ($P < 0.001$). On this basis, we disaggregated urine and dung data for the subsequent analyses.

Dung

Our analysis showed there was no significant effect of livestock type on dung EF_3 values (Table 6), with the degree of significance based on a poisson distribution ranging from 0.60 to 1.00. We also observed topography had no significant influence on dung EF_3 (Table 7), with P values ranging from 0.93 to 1.00. On this basis, dung EF_3 values were pooled to a single value of 0.12%.

Table 6. Mean dung EF_3 values and pairwise comparisons for dairy cattle, non-dairy cattle and sheep.

Treatment	EF_3 mean	Gaussian	Poisson
Dairy	0.19	A	A
Non-dairy cattle	0.12	AB	A
Sheep	0.04	B	A

Table 7. Mean dung EF_3 values and pairwise comparisons for flatland and hill country low, medium and steep slopes.

Treatment	EF_3 mean	Gaussian	Poisson
Flatland	0.13	A	A
Low slope	0.13	A	A
Medium slope	0.09	A	A
Steep slope	0.06	A	A

Urine

Our analysis showed urine EF_3 was influenced by livestock type (Table 8) and topography (Table 9). For livestock type, given the results from the two models, we grouped dairy and non-dairy cattle urine into a single category, with sheep treated separately.

Results from the two models on the effect of slope support the grouping of flatland and low slope urine EF_3 values into a single category and medium and steep slope urine EF_3 values into a single category. As noted earlier, the effect of slope on urine EF_3 is thought to be due to a combination of lower soil microbial activity and soil fertility on steeper slopes relative to low slopes (Luo et al. 2013). Our topography grouping is supported by the pairwise comparison of low and medium slope data, when examined for non-dairy cattle and sheep only (Table 10) where each livestock types have a similar number of data for each of the slope classes. Given these results, urine EF_3 values were pooled into four categories: cattle urine on flatland/low slopes; cattle urine on medium steep slopes; sheep urine in flatland/low slopes and sheep urine on medium/steep slopes.

Table 8. Mean urine EF_3 values and pairwise comparisons for dairy cattle, non-dairy cattle and sheep.

Treatment	EF_3 mean	Gaussian	Poisson
Dairy	0.95	A	A
Non-dairy cattle	0.59	A	AB
Sheep	0.32	B	B

Table 9. Mean urine EF_3 values and pairwise comparisons for flatland and hill country low, medium and steep slopes.

Treatment	EF_3 mean	Gaussian	Poisson
Flatland	1.10	A	AB
Low slope	0.69	A	A
Medium slope	0.41	B	B
Steep slope	0.01	B	AB

Table 10. Mean urine EF_3 values and pairwise comparisons for hill country low slopes and medium slopes. Data restricted to non-dairy cattle and sheep.

Treatment	EF_3 mean	Gaussian	Poisson
Low slope	0.59	A	A
Medium slope	0.28	B	B

The five pooled values are shown in Figure 7. See Table A1-2 for more detailed, tabulated values. On flatland and low slopes, sheep urine EF_3 was approximately half of the cattle EF_3, while on medium/steep slopes sheep urine EF_3 was approximately one quarter of the cattle EF_3. The effect of slope is evident, with cattle urine EF_3 on medium/steep slopes being one third of that for flatland and low slopes. A similar comparison for sheep urine showed that EF_3 for medium/steep slopes was only one sixth of that for flatland and low slopes. 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 is probably due to the steep sloping soils having lower microbial activity (Zhong et al. 2016), resulting in lower rates of nitrification and denitrification, and consequently lower N_2O emissions from urine compared to the microbial processes occurring within dung.

These findings corroborate the results of an earlier meta-analysis (Kelliher et al. 2014), showing a significant difference in EF_3 values between cattle vs sheep, low vs medium slopes, and urine vs dung. The current meta-analysis (i) used a larger database thereby providing a more robust analysis, and (ii) was expanded to contain the effect of steep slopes on dung and urine EF_3.

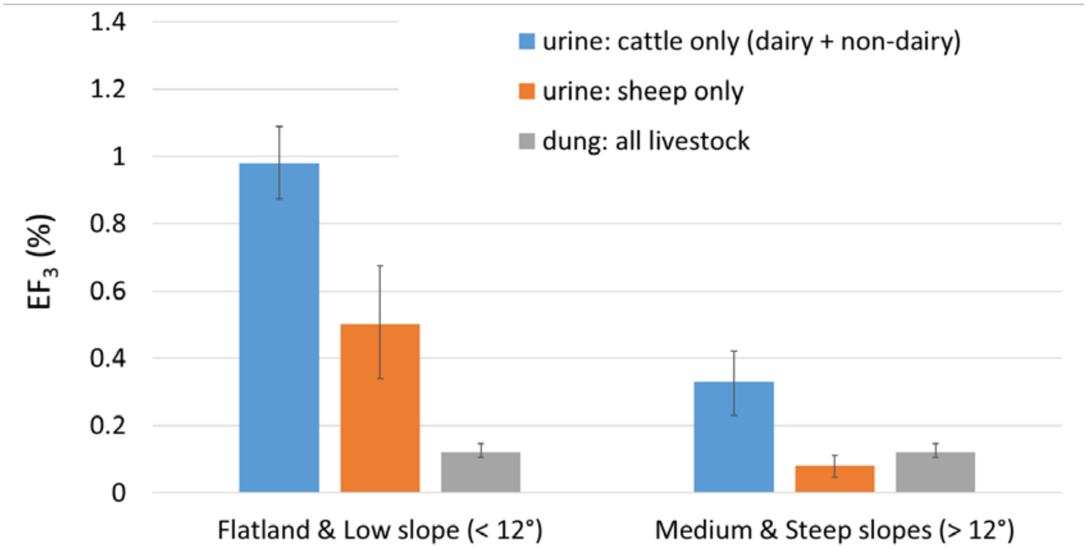

Figure 7: Emission factors (%) calculated using means pooled where values were not significantly different (Method 2). Error bars represent 95% confidence interval.

5.2 Emission factors used for assessing impact on GHG inventory

To assess the impact of updated EF_3 values for flatland and hill country soils on the national N_2O inventory, two different scenarios were assessed, based on the EF_3 values generated from the two different methods described above (Section 5.1). Each scenario included flatland and hill land EF_3 values for dairy cattle, non-dairy cattle sheep and deer. As N_2O emissions have not been measured for deer urine, deer EF_3 values were assumed to be averages of the EF_3 values for non-dairy cattle and sheep (as agreed with MPI). This approach can be justified as follows: EF_3 is related to urine volume (see section

5.1), and, per urination event, on average, cattle void larger volumes of urine than sheep (1.2 L compared to 0.5 L; Selbie et al. 2015). However, no data exists for deer urine volumes. But given urine volume is generally related to body size (i.e. the large 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. On this basis, in the absence of deer EF_3 values and deer urine volume data, we have estimated the deer EF_3 values to be the average of those for non-dairy cattle and sheep.

For comparative purposes, N_2O emissions were also estimated using the current country-specific EF_3 values for livestock urine and dung (EF_3 = 1% and 0.25%, respectively) as a baseline approach.

The two different scenarios, including the basis of the EF_3 calculation and illustration of the values used, are listed below:

- Scenario 1: Based on EF_3 values from Method 1 (Fig. 8)
- Scenario 2: Based on EF_3 values from Method 2 (Fig. 9)

Tabulated EF_3 values for each scenario are shown in Table 11.

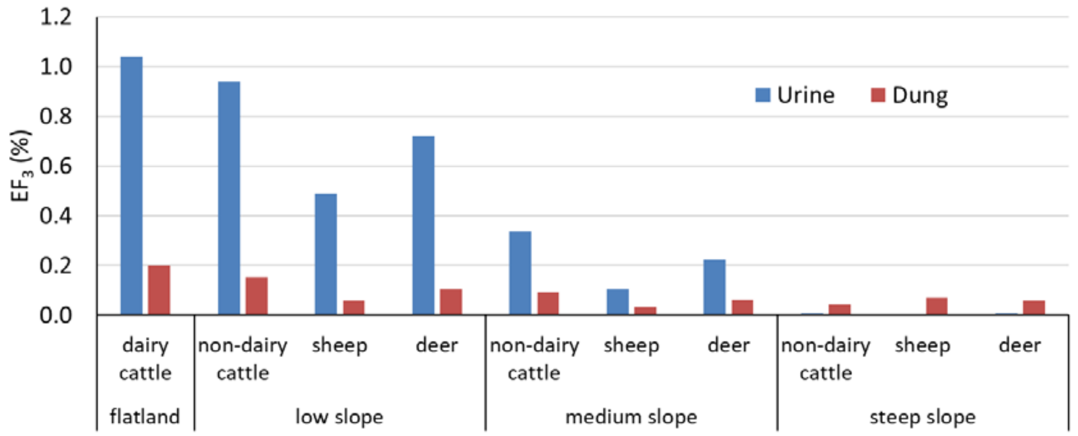

Figure 8: Scenario 1 – dairy cattle, non-dairy cattle and sheep EF_3 values based on non-pooled means, with deer EF_3 values calculated as the average for non-dairy cattle and sheep. All dairy cattle assumed to be on flatland, other livestock on low to steep hill country.

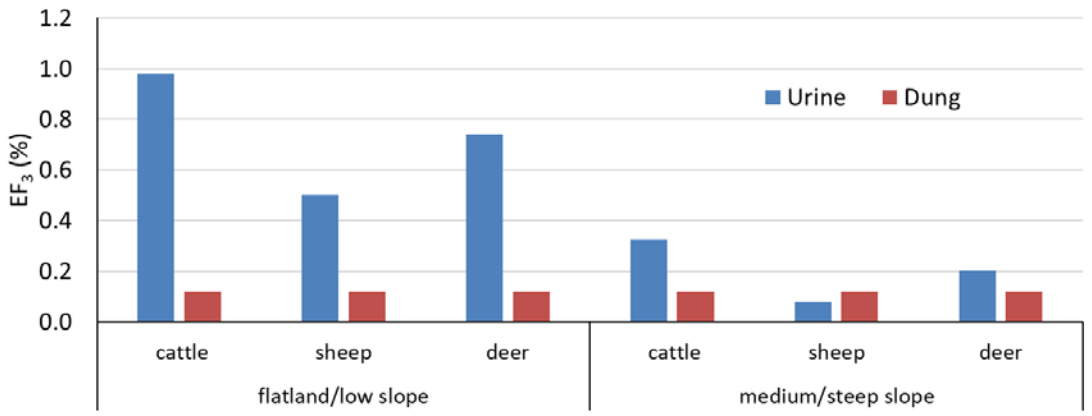

Figure 9: Scenario 2 - dairy cattle, non-dairy cattle and sheep EF_3 values based on pooled means, with deer EF_3 values calculated as the average for non-dairy cattle and sheep. All dairy cattle assumed to be on flatland, other livestock on low to steep hill country.

Table 11: Tabulated non-pooled EF_3 values (%) used in scenario 1 and pooled EF_3 values used in scenario 2.

Topography	***Livestock class***	***Scenario 1***		***Scenario 2***	
		EF dung	*EF urine*	*EF dung*	*EF urine*
flatland	all dairy cattle	0.20	1.04	0.12	0.98
low slope	non-dairy cattle	0.15	0.94	0.12	0.98
	sheep	0.06	0.49	0.12	0.50
	deer	0.11	0.72	0.12	0.74
medium slope	non-dairy cattle	0.09	0.34	-	-
	sheep	0.03	0.10	-	-
	deer	0.06	0.22	-	-
steep slope	non-dairy cattle	0.04	0.01	-	-
	sheep	0.07	0.00	-	-
	deer	0.06	0.01	-	-
medium-steep slope	non-dairy cattle	-	-	0.12	0.33
	sheep	-	-	0.12	0.08
	deer	-	-	0.12	0.20

5.3 Nitrous oxide emissions from excreta deposition

Nitrous oxide emissions calculated using the two EF scenarios and the current country-specific EF_3 values are given in Figures 10 to 13, for dairy cattle, non-dairy cattle, sheep and deer grazing pastures in 1990, 2005 and 2017.

Based on non-pooled EF_3 values (scenario 1), calculated N_2O emissions from dairy grazing flatland pastures increased by 2% across all years (Fig. 10). For non-dairy cattle grazing hill country, the non-pooled EF_3 values resulted in emissions being reduced by ~40% across all years (Fig. 11). Calculated N_2O emissions from sheep grazing hill country were reduced by ~70% across all years when using the non-pooled EF_3 values (Fig. 12). Given the deer EF values were estimated by averaging sheep and non-dairy cattle values, the reduction in calculated emissions from deer were mid-way between sheep and non-dairy cattle, at *ca* 55% of those based on the current EF_3 values (Fig. 13).

When dairy cattle, non-dairy cattle, sheep and deer are grouped together, the percentage change in calculated N_2O emissions based on the non-pooled EF_3 was dependent on the year of calculation. For example, the calculated emissions for 1990 were reduced by 46% compared to those based on the current EF_3 values. For 2017, however, calculated N_2O emssions based on the non-pooled EF_3 were reduced by only 28% compared to those based on the current EF_3 values (Fig. 14). This variation in percentage change is attributed to the increased contribution by dairy over time being greater than the reduction in calculated emissions through the use of updated EF values for non-dairy livestock (Fig. 14).

Focusing on the pooled EF_3 values (scenario 2), calculated N_2O emissions from dairy grazing flatland pastures declined by 6% across all years compared to those based on the current EF_3 values (Fig. 10). For non-dairy cattle and sheep grazing hill country, the pooled EF_3 values resulted in emissions being reduced by ~34% and ~66%, respectively, across all years compared to those based on the current EF_3 values (Fig. 11 and 12). The reduction in calculated emissions from deer were mid-way between sheep and non-dairy cattle, at *ca* 50% of those based on the current EF_3 values (Fig. 13). When dairy cattle, non-dairy cattle, sheep and deer are grouped together, the percentage change in calculated N_2O emissions based on the pooled EF_3 was similar to the changes observed from employing non-pooled EF_3 values (Fig. 14). In 1990, the calculated emissions were reduced by 44% compared to those based on the current EF_3 values whereas in 2017, calculated emissions were reduced by 30%.

An analysis of the data using 1990 as the baseline shows that total calculated N_2O emissions based on the current country-specific values in 1990 and 2017 were 17.0 and 18.2 kt N_2O, an increase of 7% (Fig. 14). Scenarios 1 and 2, however, resulted in a 42 and 33% increase, respectively, in total emissions over the same period. This large increase is due to dairy N_2O emissions more than doubling since 1990, which is greater than the reduction in calculated emissions from non-dairy livestock using the updated EF_3 values.

Overall, adopting either of the two updated EF values for dairy cattle, non-dairy cattle, sheep and deer reduced the calculated total N_2O emissions for these livestock classes (Fig. 14). More, detailed results are shown in Appendix 2.

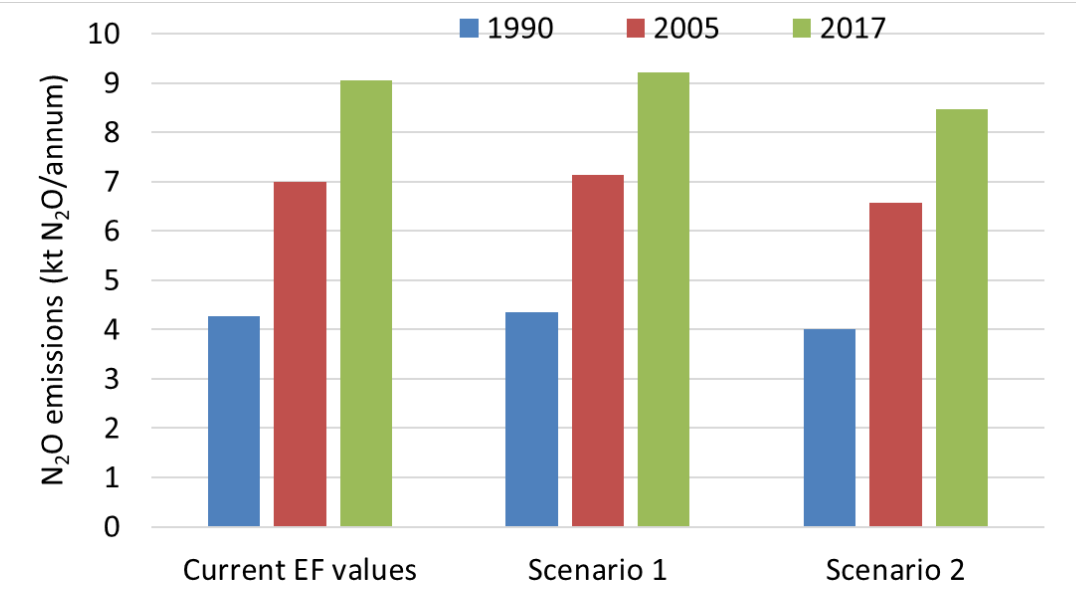

Figure 10: Change in national N_2O emissions (kt N_2O/annum) from **dairy cattle** for 1990, 2005 and 2017, estimated using livestock population data and current EF values (left) and two EF scenarios, where scenario 1 is based on individual EF_3 values (middle) and scenario 2 is based on pooled EF_3 values (right).

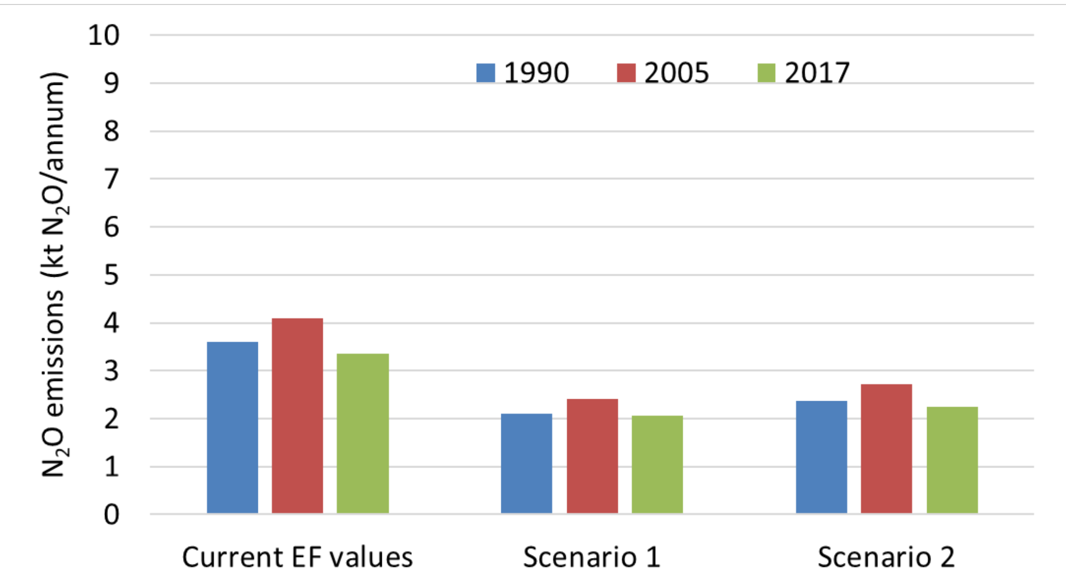

Figure 11: Change in national N_2O emissions (kt N_2O/annum) from **non-dairy cattle** for 1990, 2005 and 2017, estimated using livestock population data and current EF values (left) and two EF scenarios, where scenario 1 is based on individual EF_3 values (middle) and scenario 2 is based on pooled EF_3 values (right)..

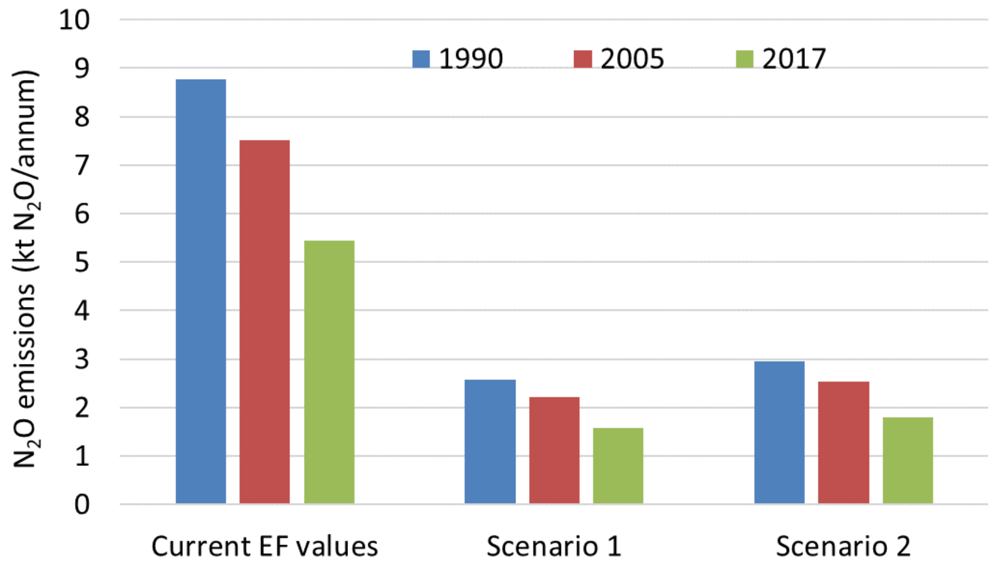

Figure 12: Change in national N_2O emissions (kt N_2O/annum) from **sheep** for 1990, 2005 and 2017, estimated using livestock population data and current EF values (left) and two EF scenarios, where scenario 1 is based on individual EF_3 values (middle) and scenario 2 is based on pooled EF_3 values (right).

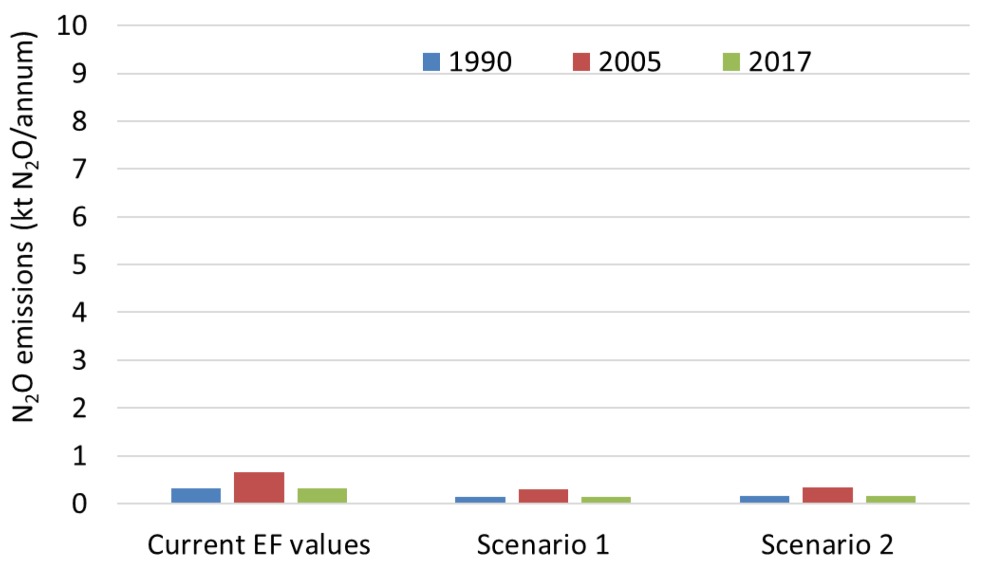

Figure 13: Change in national N_2O emissions (kt N_2O/annum) from **deer** for 1990, 2005 and 2017, estimated using livestock population data and current EF values (left) and two EF scenarios, where scenario 1 is based on individual EF_3 values (middle) and scenario 2 is based on pooled EF_3 values (right).

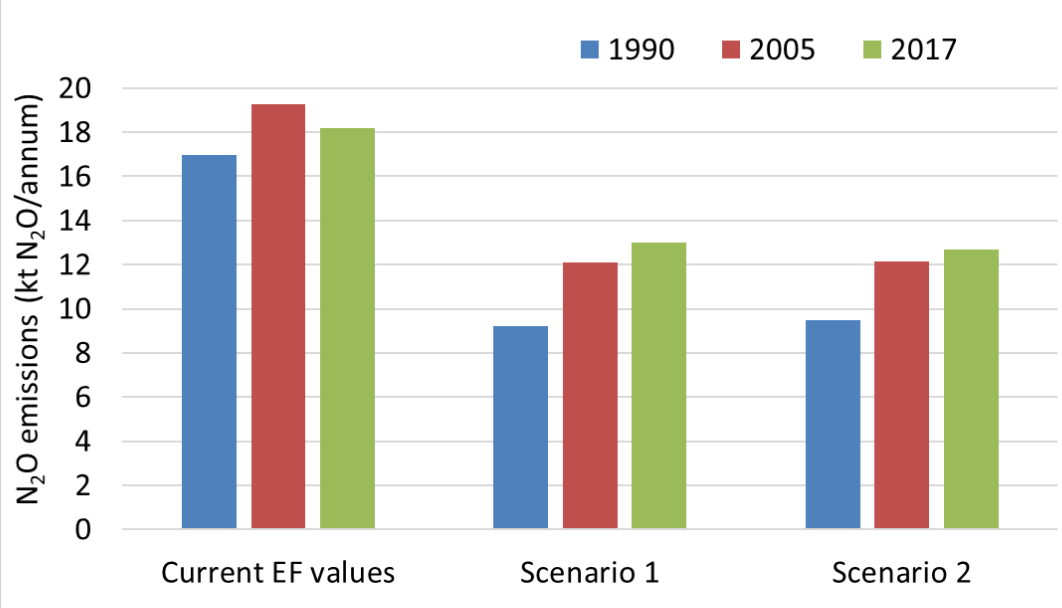

Figure 14: Change in national N_2O emissions (kt N_2O/annum) from **dairy cattle, non-dairy cattle, sheep and deer** for 1990, 2005 and 2017, estimated using livestock population data and current EF values (left) and two EF scenarios, where scenario 1 is based on individual EF_3 values (middle) and scenario 2 is based on pooled EF_3 values (right).

5.4 General Discussion

To implement the revised calculation of N_2O emissions from dung and urine deposited onto hill land (Saggar et al. 2017), MPI require recommendations on which EF_3 values to employ for non-dairy cattle, sheep and deer grazing hill country. This also provided an opportunity to updated the EF_3 values used for dairy cattle grazing flatland. As stated in Section 2, the objectives of this project were to update the EF_3 database and conduct a meta-analysis to determine the most suitable EF_3 values for dairy cattle, non-dairy cattle, sheep and deer grazing flatland and hill country pastures.

In Sections 5.1 to 5.3, we presented the results of the meta-analysis based on an updated database. We adopted two different methods for arriving at updated EF_3 values. These were:

Method 1: arithmetic means of available data for each of the 21 combinations

Method 2: arithmetic means pooled where values are not significantly different

The updated EF_3 values for excreta deposited onto pasture reduced the calculated N_2O emissions from dairy cattle, non-dairy cattle, sheep and deer in 2017 by *ca* 28-30%

compared to using the current EF_3 values. As noted in Section 5.3, the impact of using individual EF_3 values compared to five pooled EF_3 values was negligible.

When selecting the most suitable method, it needs to be acknowledged that this, in turn, will impact on the calculated N_2O emissions for the livestock sector. It is critical, however, that the selected method is based on objective reasoning, and is not influenced by the resultant calculated N_2O emissions.

We suggest that **Method 2 is the most suitable method** for calculating the updated EF_3 values for hill country. This provides a statistically-based approach to the calculation of EF_3 values, and aligns with previous meta-analysis studies (e.g. Kelliher et al. 2014).

Method 2 was the basis for Scenario 2, where deer EF_3 values were calculated as the average of non-dairy cattle and sheep values for each slope class and excreta type. On this basis, the **recommended EF_3 value for dairy cattle, non-dairy cattle, sheep and deer** for adoption in the national N_2O inventory are shown in Table 12. These are the same values presented as Scenario 2 in Section 5.2 (sourced from Table 11).

Table 12: Tabulated pooled EF values from scenario 2.

Livestock type	Excreta type	Topography	
		Flatland & Low slope (< 12°)	Medium & Steep slope (> 12°)
All livestock	Dung	0.12	
Dairy* & Non-dairy cattle	Urine	0.98	0.33
Deer	Urine	0.74	0.20
Sheep	Urine	0.50	0.08

* it is assumed all dairy excreta is deposited on to Flatland

Sheep and cattle urine was typically applied at a urine volume per patch area of 4 L/m^2 and 10 L/m^2, respectively (Luo et al. 2013). The difference in urine volume:surface area for sheep and cattle is likely to influence the uptake of urine N by pasture. At the same urine N concentration sheep urine is expected to result in more N uptake compared with cattle urine, resulting in increased N utilization as a proportion of the urine-N deposited. This may partly explain why sheep urine EF_3 values were lower than those for cattle urine. Our previous study, based on a smaller dataset, also showed that sheep urine EF_3 was significantly lower than cattle urine EF_3 (Kelliher et al. 2014).

A recent study from the UK provides support for the use of lower emission factors for extensively grazed ‘uplands and hill areas’ compared to intensively grazed pastures (Marsden et al. 2018). These workers measured EF_3 values ranging from -0.02% to 0.08% for real and artificial sheep urine deposited onto a semi-improved upland grassland in North Wales in spring and autumn. The trial sites used had a 13% gradient, which is equivalent to a 7° slope; this would lie within New Zealand’s ‘low slope’ category. The authors noted that these values are much lower than the IPCC default values of 1% for urine, and also lower than the recently derived UK-specific cattle urine value of 0.69% (Chadwick et al. 2018). Marsden et al. (2018) showed that this UK cattle urine value would not apply to sheep in ‘uplands’ (equivalent to New Zealand’s hill country), due to different climates, soils, vegetation, stocking density and livestock type. Indeed, their range of values for sheep urine grazing a ‘low slope’ (-0.02% to 0.08%) is much lower than the proposed value of 0.50% for New Zealand (Table 12), with the difference likely to be due to some of the factors listed above i.e. climate, soil and vegetation.

Estimated N_2O emissions from all grazing livestock (dairy cattle, non-dairy cattle, sheep and deer) based on the current EF values and the recommended EF values in 1990, 2005 and 2015 are shown in Table 13.

Table 13: Total (direct) N_2O emissions (kt N_2O/annum) from excreta deposition by all grazing livestock, estimated for 1990, 2005 and 2017 using current EF values and the recommended EF values for dairy cattle, non-dairy cattle, sheep and deer based on scenario 2. Current EF values based on 2019 GHG inventory (Ministry for the Environment, 2019).

Year	Current EF values	Scenario 2	Change in estimated N_2O emissions using Scenario 2 values[A] (kt N_2O/annum)	Percent change in estimated N_2O emissions using Scenario 2 values[A]
1990	17.0	9.5	-7.5	-44%
2005	19.3	12.2	-7.1	-37%
2017	18.2	12.7	-5.5	-30%

[A] negative values indicates a decrease in emissions.

The impact of the recommended EF values on estimated N_2O emissions varies by year. For instance, in 1990, the estimated N_2O emissions based on the recommended EF values are *ca* 44% of those based on the current approach, while for 2005 and 2017 the estimated emissions are reduced by 37% and 30%, respectively (Table 7). The reduced impact of the recommended EF 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 'diluting' the impact of the lower (non-dairy cattle) hill land EF values over this 27-year period.

The N loads used in field trials for determining EF_3 for non-dairy cattle urine ranged between 207 and 589 kg N/ha. The observed significant N load effect on EF_3 for non-dairy cattle urine was possibly due to the limited N loads in the studies. Nitrogen loads used for dairy urine field trials ranged from 367 to 1130 kg N/ha, which is more representative of the range in N loads reported for cattle (200 – 2000 kg N/ha; Selbie et al. 2015). We therefore suggest further experimentation using a wider range of N loads to confirm whether an N load effect exists for non-dairy cattle urine.

6. Recommendations

We suggest updated EF_3 values for flatland and hill country are based on the pooled values. This provides a statistically-based approach to the calculation of EF_3 values, and aligns with previous meta-analysis studies (e.g. Kelliher et al. 2014).

We also suggest that further experimentation using a wider range of N loads for non-dairy cattle urine is required to confirm whether an N load effect exists for this N source.

7. Acknowledgements

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8. References

Cameron KC, Di HJ, Moir JL 2014. Dicyandiamide (DCD) effect on nitrous oxide emissions, nitrate leaching and pasture yield in Canterbury, New Zealand. New Zealand Journal of Agricultural Research, 57: 251-270

Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G., Rees, R.M., 2018. The contribution of cattle urine and dung to nitrous oxide emissions: Quantification of country specific emission factors and implications for national inventories. Science of the Total Environment 635, 607-617.

de Klein, C.A.M.; Barton, L.; Sherlock, R.R.; Li, Z.; Littlejohn, R.P. (2003) Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils. Australian Journal of Soil Research 41 (3): 381-399

de Klein C.A.M., Li, Z., Sherlock, R.R (2004) Determination of the N2O and CH4 emission factors from animal excreta and urea following a winter application in 2 regions of New Zealand. Report for MAF Policy, Wellington. Pp. 27

de Klein, C.A.M.; Cameron, K.C.; Di, H.J.; Rys, G.; Monaghan, R.M.; Sherlock, R.R. (2011) Repeated annual use of the nitrification inhibitor dicyandiamide (DCD) does not alter its effectiveness in reducing N2O emissions from cow urine. Animal Feed Science and Technology 166-167: 480-491

de Klein CAM, Letica SA, MacFie P 2014. Evaluating the effects of Dicyandiamide (DCD) on nitrogen cycling and dry matter production in a 3-year trial on a dairy pasture in South Otago, New Zealand. New Zealand Journal of Agricultural Research. 57: 316-331.

de Klein CAM, Luo J, Woodward KB, Styles T, Wise B, Lindsey S, Cox N (2014). The effect of nitrogen concentration in synthetic cattle urine on nitrous oxide emissions. Agriculture Ecosystems & Environment 188: 85-92.

Hoogendoorn, C.J., de Klein, C.A.M., Rutherford, A.J., Letica, S., Devantier, B.P. (2008) The effect of increasing rates of nitrogen fertiliser and a nitrification inhibitor on the nitrous oxide emissions from urine patches on sheep grazed hill country pasture. Australian Journal of Experimental Agriculture. 48, 147-151

Hoogendoorn, C.J., Luo, J., van der Weerden, T., Saggar, S., Wise, B., Lloyd-West, C., Judge, A. (2013). Evaluation of beef cattle excreta nitrous oxide emission factors. MPI Agricultural GHG Inventory Research: Agreement Number 15425. Report prepared for MPI. Pp. 58.

Hoogendoorn, C.J., Luo, J., Lloyd-West, C.M., Devantier, B.P., Lindsey, S.B., Sun, S., Pacheco, D., Li, Y., Theobald, P.W., Judge, A., 2016a. Nitrous oxide emission factors for urine from sheep and cattle fed forage rape (Brassica napus L.) or perennial ryegrass/white clover pasture (Lolium perenne L./Trifolium repens). Agric., Ecosyst. Environ. 227, 11-23.

Hoogendoorn, C.J., Newton, P.C.D., Devantier, B.P., Rolle, B.A., Theobald, P.W., Lloyd-West, C.M., 2016b. Grazing intensity and micro-topographical effects on some nitrogen and carbon pools and fluxes in sheep-grazed hill country in New Zealand. Agric., Ecosyst. Environ. 217, 22-32.

IPCC, 2017. New Zealand Sectoral Background Data for Agriculture – Table 3As2. Common Reporting Format. https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017 Accessed 24 July 2018.

Kelliher, F.M., Cox, N., Van Der Weerden, T.J., De Klein, C.A.M., Luo, J., Cameron, K.C., Di, H.J., Giltrap, D., Rys, G. 2014. Statistical analysis of nitrous oxide emission factors from pastoral agriculture field trials conducted in New Zealand. Environmental Pollution 186, 63-66.

Ledgard SF, Luo J, Sprosen MS, Wyatt J, Balvert S, Lindsey S 2014. Effects of the nitrification inhibitor dicyandiamide (DCD) on pasture production, nitrous oxide emissions and nitrate leaching in Waikato, New Zealand. New Zealand of Agricultural Research, 57: 294-315.

Luo J, Lindsey SB & Ledgard SF (2008) Nitrous oxide emissions from animal urine application on a New Zealand pasture. Biology Fertility of Soils 44: 463-470

Luo, J., Cameron, K.C., de Klein, C.A.M., Di, H.J., , Sherlock, R.R. (2009) Effects of nitrification inhibitor on N2O emissions associated with the P21 lysimeter trial - final report. Report for MAF Policy Pp. 34 May 2009

Luo, J. de Klein, C.A.M., Di, H.J., Cameron, K., Saggar, S. & Singh, J. (2010) Effect of application of DCD with Nitrogen Fertiliser and Animal Urine on N2O Emissions. Report for MAF Policy. Pp. 21 April 2010

Luo, J., Hoogendoorn C., van der Weerden, T.J., Saggar, S., de Klein, C.A.M, Giltrap, D., Rollo., M., Rys, G. 2013. Nitrous oxide emissions from grazed hill land. Agriculture Ecosystems & Environment 181, 58-68.

Luo, J., Sun, X.Z., Pacheco, D., Ledgard, S.F., Lindsey, S.B., Hoogendoorn, C.J., Wise, B., Watkins, N.L., 2015. Nitrous oxide emission factors for urine and dung from sheep fed either fresh forage rape (Brassica napus L.) or fresh perennial ryegrass (Lolium perenne L.). Animal 9, 534-543.

Luo, J., Hoogendoorn, C., van der Weerden, T., Saggar, S., de Klein, C., Giltrap, D. 2016. Nitrous oxide emission factors for animal deposited on hill country steep slopes – Final Report. MPI Agreement number 16799. Pp. 47.

Luo J, Saggar S, van der Weerden T, de Klein C 2019. Quantification of nitrous oxide emissions and emission factors from beef and dairy cattle excreta deposited on grazed pastoral hill lands. Agriculture, Ecosystems and Environment 270-271: 103-113.

Mackay AD, Saggar S, Trolove SN, Lambert MG (1995). Use of an unsorted pasture sample in herbage testing for sulphur, phosphorus and nitrogen. *New Zealand Journal of Agricultural Research* 38: 483–493.Marsden KA, Jones DL, Chadwick DR 2016. Disentangling the effect of sheep urine patch size and nitrogen loading rate on cumulative N_2O emissions. Animal Production Science 56, 265-275.

Marsden, K.A., Holmberg, J.A., Jones, D.L., Chadwick, D.R., 2018. Sheep urine patch N_2O emissions are lower from extensively-managed than intensively-managed grasslands. Agriculture Ecosystems & Environment 265, 264-274.

Ministry for the Environment 2019. New Zealand's Greenhouse Gas Inventory 1990-2017. www.mfe.govt.nz ISBN: ISSN 1179-223X (electronic). Publication number: ME 1411. Pp. 481.

Saggar S, Mackay AD, Hedley MJ, Lambert MG, Clark DA (1990). A nutrient transfer model to explain the fate of phosphorus and sulphur in a grazed hill country pasture. Agriculture Ecosystems & Environment 30, 295–315.

Saggar, S., Giltrap, D.L., Davison, R., Gibson, R., DeKlein, C., Rollo, M., Ettema, P., Rys, G. 2015. Estimating direct N_2O emissions from sheep, beef, and deer grazed pastures in New Zealand hill country: accounting for the effect of land slope on the N_2O emission factors from urine and dung. Agriculture Ecosystems & Environment 205, 70–78.

Selbie, D.R., Buckthought, L.E., Shepherd, M.A., 2015. The Challenge of the Urine Patch for Managing Nitrogen in Grazed Pasture Systems. Advances in Agronomy, pp. 229-292.

Sherlock, R.R, de Klein C.A.M., Li, Z. (2003) Determination of the N2O and CH4 emission factors from animal excreta, following a spring application in 3 regions of New Zealand. Report for MAF Policy, Wellington. Pp. 28

Sherlock, R.R, de Klein C.A.M., Li, Z. (2003) Determination of the N2O and CH4 emission factors from animal excreta, following a summer application in 3 regions of New Zealand. Report for MAF Policy, Wellington. Pp. 27

van der Weerden, T.J., Luo, J., de Klein, C.A., Hoogendoorn, C.J., Littlejohn, R.P., Rys, G.J. (2011). Disaggregating nitrous oxide emission factors for ruminant urine and dung deposited onto pastoral soils. Agriculture Ecosystems & Environment 141, 426-436.

van der Weerden, T.J., Cox, N., Luo, J., Di, H.J., Podolyan, A., Phillips, R.L., Saggar, S., de Klein, C.A.M., Ettema, P., Rys, G. (2016). Refining the New Zealand nitrous oxide emission factor for urea fertiliser and farm dairy effluent. Agriculture Ecosystems & Environment 222, 133-137.

Zhong, L., Hoogendoorn, C.J., Bowatte, S., Li, F.Y., Wang, Y., Luo, D., 2016. Slope class and grazing intensity effects on microorganisms and nitrogen transformation processes responsible for nitrous oxide emissions from hill pastures. Agric., Ecosyst. Environ. 217, 70-78.

Appendix 1

Table A1-1: Non-pooled emission factors (%, mean and 95% confidence interval (CI)) calculated for 21 combinations of excreta type, livestock type and topography (Method 1). Shaded boxes indicate no data.

Livestock type	Excreta type		Topography			
			Flatland	Low slope (< 12°)	Medium slope (12 - 24°)	Steep slope (> 24°)
Dairy cattle	Urine	Mean	1.04	0.73	0.61	
		95% CI	0.90–1.19	0.57-0.89	0.36-0.86	
	Dung	Mean	0.20	0.16	0.16	
		95% CI	0.16-0.27	0.12-0.21	0.10-0.23	
Non-dairy cattle	Urine	Mean	2.14	0.94	0.34	0.01
		95% CI	1.66-2.62	0.71-1.17	0.22-0.46	-0.01-0.03
	Dung	Mean		0.15	0.09	0.04
		95% CI		0.10-0.22	0.05-0.13	0.01-0.07
Sheep	Urine	Mean	0.52	0.49	0.10	0.00
		95% CI	0.25-0.78	0.29-0.71	0.06-0.15	-0.02-0.03
	Dung	Mean	0.03	0.06	0.03	0.07
		95% CI	0.00-0.07	0.01-0.19	0.01-0.06	-0.04-0.18

Table A1-2: Pooled emission factors (%, mean and 95% confidence interval (CI)) calculated for excreta type, livestock type and topography where values were not significantly different (Method 2).

<table>
<tr><th rowspan="2">Livestock type</th><th rowspan="2" colspan="2">Excreta type</th><th colspan="2">Topography</th></tr>
<tr><th>Flatland & Low slope (< 12°)</th><th>Medium & Steep slopes (> 12°)</th></tr>
<tr><td rowspan="2">All livestock</td><td rowspan="2">Dung</td><td>Mean</td><td colspan="2">0.12</td></tr>
<tr><td>95% CI</td><td colspan="2">0.11-0.15</td></tr>
<tr><td rowspan="2">Cattle (dairy + non-dairy)</td><td rowspan="2">Urine</td><td>Mean</td><td>0.98</td><td>0.33</td></tr>
<tr><td>95% CI</td><td>0.87-1.09</td><td>0.23-0.42</td></tr>
<tr><td rowspan="2">Sheep</td><td rowspan="2">Urine</td><td>Mean</td><td>0.50</td><td>0.08</td></tr>
<tr><td>95% CI</td><td>0.34-0.67</td><td>0.05-0.11</td></tr>
</table>

Appendix 2

Table A2-1: N_2O emissions (kt N_2O/annum) from excreta deposition by grazing livestock, estimated for 1990, 2005 and 2017 using current EF values and two EF scenarios.

Scenario	Year	Dairy cattle		Non-dairy cattle		Sheep		Deer		Total		Total
		Urine	Dung	Urine	Dung	Urine	Dung	Urine	Dung	Urine	Dung	Excreta
Current EF values	1990	3.92	0.35	3.27	0.34	7.80	0.97	0.29	0.03	15.27	1.70	16.97
	2005	6.41	0.59	3.70	0.38	6.69	0.83	0.60	0.06	17.40	1.87	19.27
	2017	8.25	0.80	3.04	0.31	4.84	0.60	0.30	0.03	16.42	1.75	18.17
Scenario 1	1990	4.08	0.28	1.95	0.16	2.37	0.21	0.14	0.01	8.52	0.67	9.19
	2005	6.67	0.47	2.24	0.18	2.04	0.18	0.28	0.02	11.23	0.86	12.09
	2017	8.58	0.64	1.91	0.15	1.46	0.13	0.14	0.01	12.07	0.93	13.01
Scenario 2	1990	3.84	0.17	2.21	0.16	2.49	0.47	0.15	0.01	8.69	0.81	9.50
	2005	6.28	0.28	2.53	0.18	2.14	0.40	0.31	0.03	11.25	0.90	12.15
	2017	8.08	0.39	2.10	0.15	1.51	0.29	0.15	0.01	11.83	0.84	12.67

Table A2-2: N_2O emissions (kt carbon dioxide equivalents (CO_2e) per annum) from excreta deposition by grazing livestock, estimated for 1990, 2005 and 2017 using current EF values and two EF scenarios.

Scenario	Year	Dairy cattle		Non-dairy cattle		Sheep		Deer		Total		Total
		Urine	Dung	Urine	Dung	Urine	Dung	Urine	Dung	Urine	Dung	Excreta
Current EF values	1990	1168	106	973	101	2323	290	87	8	4552	506	5058
	2005	1910	177	1103	114	1993	249	179	17	5185	557	5742
	2017	2457	240	905	93	1442	179	88	9	4892	522	5414
Scenario 1	1990	1215	85	580	48	705	63	41	3	2540	199	2739
	2005	1986	142	667	54	609	53	85	6	3347	256	3603
	2017	2556	192	568	46	434	37	41	3	3598	278	3876
Scenario 2	1990	1145	51	659	49	741	139	44	4	2589	243	2831
	2005	1872	85	754	55	636	119	92	8	3354	267	3621
	2017	2408	115	625	45	449	86	44	4	3526	250	3777