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Review of summer values for nitrous oxide emissions – final report

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September 2016

REPORT FOR MINISTRY FOR PRIMARY INDUSTRIES

CLIENT REPORT NUMBER: RE500/2016/083

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1. Executive Summary

The objective of this review was to determine whether additional summer field trials are required in order to improve the accuracy of emission estimates in New Zealand's national nitrous oxide (N_2O) inventory. To achieve this objective, firstly, we updated and analysed the emission factor (EF) dataset for seasonal differences in EF_3 (N_2O lost as a percentage of urine and dung N excreted) and EF_1 (N_2O lost as a percentage of fertiliser N applied) value. We also determined how EF values may be influenced by variables such as region, soil drainage class, excreta type, topography and relative rainfall. Secondly, we modelled the effect of employing seasonal EF_3 values on the total N_2O emissions from excreta deposition, providing an insight into the influence of a more accurate inventory structure on estimates of annual N_2O emissions. From these two key steps, we were able to assess if sufficient data exists for determining a summer EF value (and associated seasonal EF values) or if further field studies would be justified given the modelled impact of a more accurate inventory.

Data Collation and Analysis

Following an update of the existing EF_3 and EF_1 dataset, the number of summer EF_3 values represented only 13% of the total EF_3 dataset while summer EF_1 values were only 9% of the total EF_1 dataset.

Seasonality had a significant effect on both urine and dung EF_3, with winter producing the highest EF_3 values and summer producing the second highest EF_3 values. The mean summer EF_3 value for urine was 1.00%, whereas, winter, autumn and spring had mean values of 1.10%, 0.87% and 0.40%, respectively. For dung, summer and winter had the highest mean EF_3 value (0.23 and 0.26%, respectively), while the autumn was 0.10% and spring was lowest, at -0.18%.

When urine and dung were disaggregated into individual livestock classes, there was a significant seasonal variation in dairy dung EF_3, with a mean summer and spring value of 0.17% lying between the higher autumn value of 0.53% and lower winter value of 0.09%. There was a non-significant seasonal variation in EF_3 for dairy cattle urine, beef urine and dung, and sheep urine and dung.

An analysis of the data showed that soil drainage class, topography, region and relative rainfall had a significant effect on seasonal EF_3. However, due to the unbalanced nature of the dataset, interpretation of some of the significant effects was challenging.

There was no significant seasonal effect on urea fertiliser EF_1, although the overall mean summer EF_1 value was 0.07%, which was the lowest of all seasons (and 18 times lower than the winter value of 1.27%). Region has a significant effect on seasonal EF_1 values, whereas drainage class, topography and relative rainfall did not influence seasonal urea EF_1 values.

A recently completed, separate review on the effect of irrigation on N_2O emissions found there was evidence that irrigated soils emit more N_2O, however the magnitude of its effect was variable (Thomas et al. 2016). Limited or no data made it difficult to provide 'irrigation' EF values for urine, dung and urea fertiliser.

We conducted an uncertainty analysis of summer EF_3 and used the results to compare the effect of employing annual or seasonal EF_3 values on the 95% confidence interval (CI) of the national N_2O inventory for livestock grazing. When a single annual EF_3 value was used, the estimated 95% CI of the N_2O inventory was ± 89%. However, when seasonal EF_3 values were used, the 95% CI increased by nearly a factor of two to ± 158%. As expected, using seasonal EF_3 values increases the uncertainty, however the accuracy of the national inventory would be improved.

Modelling the effect of a Summer EF_3 on the National N_2O Inventory

The effect of employing summer (and other seasonal) EF_3 values on the national N_2O inventory for grazing livestock was modelled using a spreadsheet-based inventory model. We estimated seasonal EF_3 values using two approaches: the first based on modelling of soil water content and corrected for temperature effects ($EF_{3\ SWC}$) and the second based on analysis of the current dataset ($EF_{3\ DS}$). A direct comparison of the two approaches, using dairy urine on lowland as the N source, showed comparable EF_3 values for autumn, winter and spring. However, there was a significant difference in the values for summer, suggesting further research is required to improve the estimation of summer EF_3.

When national N_2O emissions were modelled using seasonal $EF_{3\ SWC}$ values, estimation of annual livestock N_2O emissions declined by 0.6% compared to losses based on annual EF_3 values. When seasonal $EF_{3\ DS}$ values were used, i.e. EF_3 values based on the analysis of the current dataset, estimation of annual livestock N_2O emissions declined by 8.6% compared to estimated losses using annual EF_3 values. Using the current dataset to estimate EF_3 would provide a more accurate estimation of the inventory, given both nitrogen excreta data (N_{ex}) and EF_3 values were disaggregated by livestock class, slope class, season, as well as excreta type. However, the current dataset has a limited amount of summer EF_3 data (such as dairy urine). By expanding the summer EF_3 dataset, it will be possible to generate more robust estimates of summer EF_3 values. Employing seasonal EF_3 values within the national inventory methodology is likely to improve the accuracy of the inventory.

Recommendations

Based on our review, there is currently insufficient data to justify the adoption of seasonal EF_3 values for estimating emissions within the national inventory, primarily due to a limited amount of summer EF_3 data. We have identified knowledge gaps and prioritized future work to address these gaps.

1. Dairy excreta currently represent *ca.* 50% of N_2O emissions from livestock excreta. With the proposed changes to the inventory methodology for sheep, beef and deer, and assuming livestock numbers do not change disproportionately, the contribution of dairy cattle to total N_2O emissions will increase markedly. Given that the majority of dairy cattle graze lowland pastures and the current available summer data for this N source is limited to two field studies providing a total of 17 replicate-level values, we recommend summer field trials are conducted across representative regions to improve our estimation of dairy cattle urine and dung EF_3.
2. There is a need to improve our knowledge on the influence of irrigation on summer N_2O EF_3 and EF_1. We recommend summer field trials in regions where irrigation represents a significant proportion of pastoral land. N sources should focus on dairy excreta and urea fertiliser. In addition, non-irrigated treatments should be included to improve our understanding of the impact of irrigation on N_2O emissions.
3. We have identified summer sheep EF_3 data as a knowledge gap. We recommend field trials are conducted in summer across key regions to quantify N_2O EF_3 for this N source for all three slope classes.
4. Field trials under controlled conditions (e.g. controlled ‘rainfall’) will assist in understanding the drivers of variability between soils (e.g. contrasting drainage classes) and N sources for different seasons.

While not specifically related to summer EF knowledge gaps, our analysis showed large regional variation in EF_3 values. Therefore, we suggest future research projects carefully consider selecting appropriate regions that are representative of livestock numbers and are additional to those currently used. An example of a field experiment adopting this approach is the recently initiated dairy and beef hill country experiment, where field trials are under way in Northland, and trials next year are planned for Bay of Plenty.

2. Introduction

Excreta deposition by grazing livestock represented 81% of N applied to New Zealand soils in 2014, making this the single largest source of New Zealand's agricultural nitrous oxide (N_2O) emissions (Ministry for the Environment, 2016). Currently New Zealand uses country-specific, annual emission factors (EF_3) for N_2O emissions from excreta deposited by grazing livestock, where urine has an EF_3 value of 1% and dung has an EF_3 value of 0.25% (Ministry for the Environment, 2016). New Zealand also employs a country-specific annual emission factor of 0.48% (EF_1) for urea fertiliser application to soils (Ministry for the Environment, 2016). Both values were calculated from a dataset generated from plot-scale field studies conducted in several regions across New Zealand (Luo et al. 2009; Kelliher et al. 2014a). Excreta deposition in summer represents 31% of the annual excreta-N, which compares with 24%, 21% and 24% for autumn, winter and spring. However, there is limited summer EF_3 data available for estimating the N_2O emissions during this season. Furthermore, while N fertiliser is most commonly applied in spring (J. Morton, pers. comm.), the increasing area of pasture receiving irrigation is likely to increase the amount of N fertiliser applied in the summer months. As for excreta, information on summer EF_1 is limited. More EF_3 and EF_1 data may be required to improve the estimation of the inventory accurately.

The objective of this review was to determine whether additional summer field trials are required in order to improve the accuracy of emission estimates in New Zealand's national greenhouse gas (GHG) inventory. To achieve this objective, we firstly updated and analysed the EF_3 and EF_1 dataset for seasonal differences in EF values, as well as determined how EF values may be influenced by variables such as region, soil drainage class, excreta type, topography and relative rainfall. The original dataset was collated for an earlier MPI study on the influence of key variables on N_2O EF values (Kelliher et al. 2011, 2014a). Their original dataset included 128 EF_3 and EF_1 field measurement trials for dairy cattle and sheep urine, dairy cattle and sheep dung and urea fertiliser. When examined at a seasonal level, there were only 3 field trials that began in summer, compared to 25, 40 and 60 trials which began in autumn, winter and spring, respectively. Their statistical analysis showed no seasonal effect on EF values. Since the earlier analysis by Kelliher et al. (2014a) further field trials quantifying EF values for excreta and urea fertiliser have been conducted, with one excreta study conducted in summer (unpubl. data, J. Luo, pers. comm.).

Secondly, we modelled the effect of employing seasonal EF values on the total N_2O emissions from fertiliser and excreta deposition, providing an insight into the influence of a more accurate inventory structure on estimates of annual N_2O emissions. From these two key steps, we assessed if sufficient data exists for determining a summer EF value (and associated seasonal EF values) and whether further field studies are justified given the modelled impact of a more accurate inventory.

3. Project Objectives

- To update the compilation of all available EF_3 and EF_1 data from field trials
- To compare overall summer EF_3 and EF_1 values with other seasonal EF values
- To analyse the influence of soil drainage class, slope, region, relative rainfall and any other relevant factors on seasonal EF values
- To include the effects of irrigation on summer EF_3 by sourcing relevant information from the recently completed project '*Methodology and implications of incorporating irrigation into New Zealand's inventory*' (Thomas et al. 2016).
- To provide a limited analysis of the uncertainty of the summer EF_3 value
- To model contrasting inventory scenarios to determine the impact of a summer EF_3 value on the national N_2O inventory.

4. Data Collation and Analysis

An existing dataset of all available NZ field trial data at the replicate level pertaining to N_2O emission factors for excreta deposition onto pasture (EF_3) and fertiliser application (EF_1) was updated. The N sources of interest include dung and urine deposited by dairy cattle, beef cattle and sheep, and urea fertiliser. New data was limited to studies using fresh urine and dung (as opposed to synthetic urine). Irrigation studies were also excluded as a separate analysis focusing on the effects of this farm activity on N_2O emissions has already been conducted recently (Thomas et al. 2016). Urea is the major form of synthetic N fertiliser applied to New Zealand pastures, representing 86% of all N fertiliser used (Ministry for the Environment, 2016). Consequently, the majority of studies determining N_2O emissions from N fertiliser focus on this form, and so too was our collation of field data.

4.1 Data Collation

The existing dataset, compiled by Kelliher et al. (2014a), included 529 urine, 272 dung and 181 urea fertiliser replicate-level EF values (Table 1). We updated the dataset using field experimental results obtained from published papers (Di et al. 2016; Hoogendoorn et al. 2016; Luo et al. 2015a and van der Weerden et al. 2016a) or from available client reports (Luo et al. 2015b; van der Weerden and Rutherford 2015). We also included data from a single study that has yet to be published/reported (J. Luo, pers. comm.). In total, we added 150 urine, 84 dung and 24 urea fertiliser replicate-level EF values to the dataset: further details of the updated dataset are provided below (sections 4.1.1 and 4.1.2).

Table 1 Original number of replicate-level EF_1 and EF_3 values for each season, used for meta-analysis by Kelliher et al. (2014a).

N source	Autumn	Winter	Spring	Summer	Total
Urine	176	97	184	72	529
Dung	64	72	76	60	272
Total excreta	240	169	260	132	801
Urea fertiliser	42	49	64	17	172

4.1.1 Data fields recorded

Collated data at the replicate level included the cumulative N_2O loss (kg N_2O-N/ha) from the N source (excreta or fertiliser), an associated control (nil N and nil water applied) and the N load (kg N/ha). From this, we calculated the emission factor (EF):-

$$EF = \frac{N\ source\ N_2O - Control\ N_2O}{N\ source\ applied} \times 100\%$$

where EF is the emission factor (N_2O-N emitted as a % of N applied) for urine or dung (EF_3) or urea fertiliser ($EF_{1\ UREA}$, hereafter referred to as EF_1). N source N_2O is the cumulative N_2O emissions from urine or dung or fertiliser N_2O (kg N_2O-N/ha) and Control N_2O is the cumulative N_2O emissions from the control plots (kg N_2O-N /ha), and N source applied is the rate of N applied (kg N/ha).

Other key data captured in the dataset included:-

- Topography (lowland vs hill country low slope (< 12 °) vs hill country medium slope (12 – 24 °) vs hill country steep slope (> 24 °)),
- Soil drainage class (free vs. poor)
- Trial start date
- Region (based on regional authority)
- Cumulative rainfall in first 30 days of the trial (used to determine whether trials were conducted under typical or atypical moisture conditions).

Topography was divided into lowland, which is primarily grazed by dairy cattle, and hill country (primarily grazed by beef cattle, deer and sheep). Hill country has been divided into three slope categories: low (< 12 °), medium (12 – 24 °) and steep (>24 °).

We followed the same approach adopted by Kelliher et al. (2014a) in defining soil drainage class, season and relative rainfall. The field trials and sites were classified according to 2 drainage classes (free and poor), based on the New Zealand Soils Classification (Hewitt, 2010). Soil drainage is a relatively simple classification of the soil profile, based on the visual occurrence of waterlogging and chemical reduction to describe the likelihood of seasonal wetness (Webb and Lilburne, 2011).

Each trial was classified by season by determining which month the trial's 15th day occurred as follows: Jan, Feb and Dec for summer, Mar, Apr and May for autumn, Jun, Jul and Aug for winter and Sep, Oct and Nov for spring. The 15th day of the trial generally represents the period of the highest N_2O fluxes following the application of an N source.

The relative rainfall associated with each trial provides an assessment of how typical the moisture conditions were during the trial. For each trial, cumulative rainfall for 30 days following treatment application was recorded. These rainfall values were then divided by the long-term monthly rainfall statistics, obtained from the closest weather station (Kelliher et al. 2014a). These ratios (i.e. actual rainfall over the first 30 days of the trial / long-term average rainfall for the same period) were grouped into five relative rainfall categories: very low (<0.6), low (0.6-0.8), average (0.8-1.2), high (1.2-1.8) and very high (>1.8) (van der Weerden et al. 2014), with 'low' and 'very low' indicating the conditions were drier or much drier, and 'high' and 'very high' indication that conditions were wetter or much wetter, than the long-term average.

Although topsoil Olsen P levels has previously been used as a proxy of potential effects of soil fertility on N_2O emissions, due to the connection between the N and P cycles (Kelliher et al. 2011), this variable was excluded from our database, as many of the lowland sites did not include Olsen P data.

We also excluded the single study conducted on peat soil as N_2O emissions from this organic soil are a-typical. In addition, one field study with 4 replicates of a urea treatment was excluded because this trial was considered as an outlier due to the unusually high EF_1 values (emission factors of up to 15%). Both studies were also excluded in previous analysis (Kelliher et al. 2014a).

4.1.2 Number of data

We collated 1307 replicate-level EF_3 and EF_1 values, with urine and dung EF_3 values totalling 679 and 356 values, respectively, and urea fertiliser totalling 196 EF_1 values (Table 2).

The distribution of EF_3 values across the seasons showed that summer had the least number of trials (Table 2). For urine, there were 77 values for summer (37 for dairy and 40 for beef), which was less than half compared to other seasons. Autumn had the largest number of urine values, at 265, while winter and spring each had 149 and 188 urine values. For dung EF_3 values, the distribution of values across seasons was a little more even, although summer still had the least number, at 60, compared to 104, 112 and 80 for autumn, winter and spring, respectively (Table 2).

Table 2 Number of replicate-level EF_1 and EF_3 values for each season.

N source	Autumn	Winter	Spring	Summer	Total
Dairy urine	177	93	104	37	411
Dairy dung	14	40	36	20	110
Beef urine	20	28		40	88
Beef dung	40	28	8	40	116
Sheep urine	68	28	84		180
Sheep dung	50	44	36		130
Total Urine	265	149	188	77	679
Total Dung	104	112	80	60	356
Total Excreta	369	261	268	137	1035
Urea fertiliser	42	49	88	17	196

For urea fertiliser trials, summer contained the least number of data points, at 17 replicate-level EF_1 values, representing only 9% of the urea dataset. This was less than half of the number of values for autumn (42) and winter (49), while spring had the largest number of values (88 or 45% of the dataset; Table 2).

The summer urine EF_3 values were limited to dairy on lowland (17) and hill country low slopes (20), and beef on hill country low slopes (20) and medium slopes (20) (Table 3). Summer dung EF_3 values were limited to hill country only, with dairy dung on low slopes (20) and beef dung on both low and medium slopes (20 values each), with no data available for dairy or beef dung on lowland.

Table 3 Number of replicate-level EF_3 values for each topography class and season.

N source	Topography	Autumn	Winter	Spring	Summer	Total
Dairy urine	Lowland	151	79	76	17	323
	H/C[A] - low slope	26	14	28	20	88
	H/C - medium slope					
	H/C - steep slope					
Dairy dung	Lowland	14	34	36		84
	H/C - low slope		6		20	26
	H/C - medium slope					
	H/C - steep slope					
Beef urine	Lowland		8			8
	H/C - low slope				20	20
	H/C - medium slope	10	10		20	40
	H/C - steep slope	10	10			20
Beef dung	Lowland					
	H/C - low slope	20	8	8	20	56
	H/C - medium slope	10	10		20	40
	H/C - steep slope	10	10			20
Sheep urine	Lowland	8	8	20		36
	H/C - low slope	20		44		64
	H/C - medium slope	30	10	20		60
	H/C - steep slope	10	10			20
Sheep dung	Lowland	10	16	28		54
	H/C - low slope	20	8	8		36
	H/C - medium slope	10	10			20
	H/C - steep slope	10	10			20
Total		369	263	268	137	1035

[A]H/C = Hill Country

4.2 Data Analysis

We used the computing package 'R' (R core team, 2015) to conduct the statistical analysis of the data. Models with both fixed and random effects were fitted. The fixed effects were season, N excreta type and the variable of interest (season, soil drainage class, slope, region, relative rainfall). The remaining variables were fitted as random effects. Models including all possible interactions of the fixed effects were fitted and the best model chosen by comparing Akaike information criteria (AIC) and deviance statistics. The random effects were kept the same in the model building process. 95% confidence intervals were found by bootstrap simulations, these are reported although the back transformation and bias adjustment may render them less accurate.

The data were separated into EF_3 and EF_1 and, because there were several negative seasonal EF values, were adjusted by adding an *a* term to ensure the negative values were positive prior to log transformation and testing for significant differences by comparing the deviance of models with and without the additional variable. For EF_3 data, we initially fitted N excreta type (urine vs dung) as a fixed term with all other variables (season, soil drainage class, slope, region, relative rainfall) as random effects. Excreta type was then disaggregated by livestock type to examine seasonal variation of their respective EF_3 values. We then pooled the excreta data into dung and urine to individually assess the influence of each variable (soil drainage class, slope, region, relative rainfall) on seasonal EF_3 values.

For EF_1 data, we fitted season as a fixed term with all other variables (soil drainage class, slope, region, relative rainfall) as random effects.

Finally, for both EF_3 and EF_1, we obtained best linear unbiased predictors (BLUPs) to determine the magnitude of the effect of each variable and their interaction with N excreta type on $\ln(EF_3)$ and the effect of each variable on $\ln(EF_1)$. These BLUPs were then back transformed, followed by subtraction of the *a* term, and bias corrected so that the predicted means and raw means were consistent.

4.3 Results and Discussion

4.3.1 Considerations on the statistical analysis

Our analysis relied on the individual assessment of the influence of key variables on seasonal EF_3 and EF_1 values while remaining variables were fitted as random effects. This approach was appropriate because, whilst each study was a designed experiment, when they are grouped together the resulting data set is very unbalanced in the auxiliary variables. We can draw strength from related studies by including these variables as random effects.

The consequence of adopting this approach is that the influence of random variables will influence the output; the degree of influence will depend on the amount of data available for a particular group in the data set. Our dataset shows considerable imbalance in the auxiliary variables, making it more difficult to interpret the output for a given variable. Consideration also needs to be given to the unbalanced nature of the dataset when interpreting the data. Ideally, the analysis would be conducted on a dataset that has the same number of EF values for every combination of N source, season, topography, region and relative rainfall. This of course is not the current situation, and therefore planning of any future field trials should aim to improve the spread of values across combinations, with a particular focus on where there are no or very few data. Clearly, variables such as rainfall cannot be set for a particular trial and other approaches such as artificial watering may need to be considered. Further, some combinations of the auxiliary variables will not occur in practice, for example dairy dung and urine on steep hill country, and these combinations should therefore not be considered. The graphs depict the raw data rather than the predicted values from the model. They illustrate the skewness of the data and some outliers, demonstrating the large variability in the measured values. There were several negative EF values within the dataset: all data was adjusted to ensure the negative values were positive prior to transforming in the analysis.

4.3.2 Influence of excreta type and livestock class on seasonal EF_3

Urine EF_3 was significantly greater than dung EF_3 ($P < 0.001$), as shown in previous analysis (e.g. Kelliher et al. 2014a; van der Weerden et al. 2014). Season was found to have a significant effect on both urine and dung EF_3 ($P = 0.011$; Fig. 1; Table 4). This is in contrast to an earlier statistical analysis of a smaller dataset showing no significant seasonal variation ($P = 0.379$; see Table 2 in van der Weerden et al. 2014). While the statistical approaches were similar but not identical, we suspect the reason for this change is the increase in the number of data in some seasons.

In the current analysis, winter produced the highest urine EF_3 mean of 1.10%, whereas spring produced the lowest, at 0.40% while summer and autumn had mean values of 1.00% and 0.87%, respectively (Table 5). For dung EF_3, winter also produced the highest value, at 0.26%, which was a little more than the summer mean of 0.23%. Autumn had a mean value of 0.10%. In contrast, spring produced a negative mean dung EF_3 value of -0.18% (Table 5). There was no interaction between N excreta type and season ($P = 0.146$; Table 4). This may reflect the average soil moisture and temperature conditions for the different seasons: the highest emissions in winter may be due to the wet soils, while summer produces the second highest EF_3 values possibly due to warmer summer conditions stimulating soil microbial activity, particularly following rainfall events.

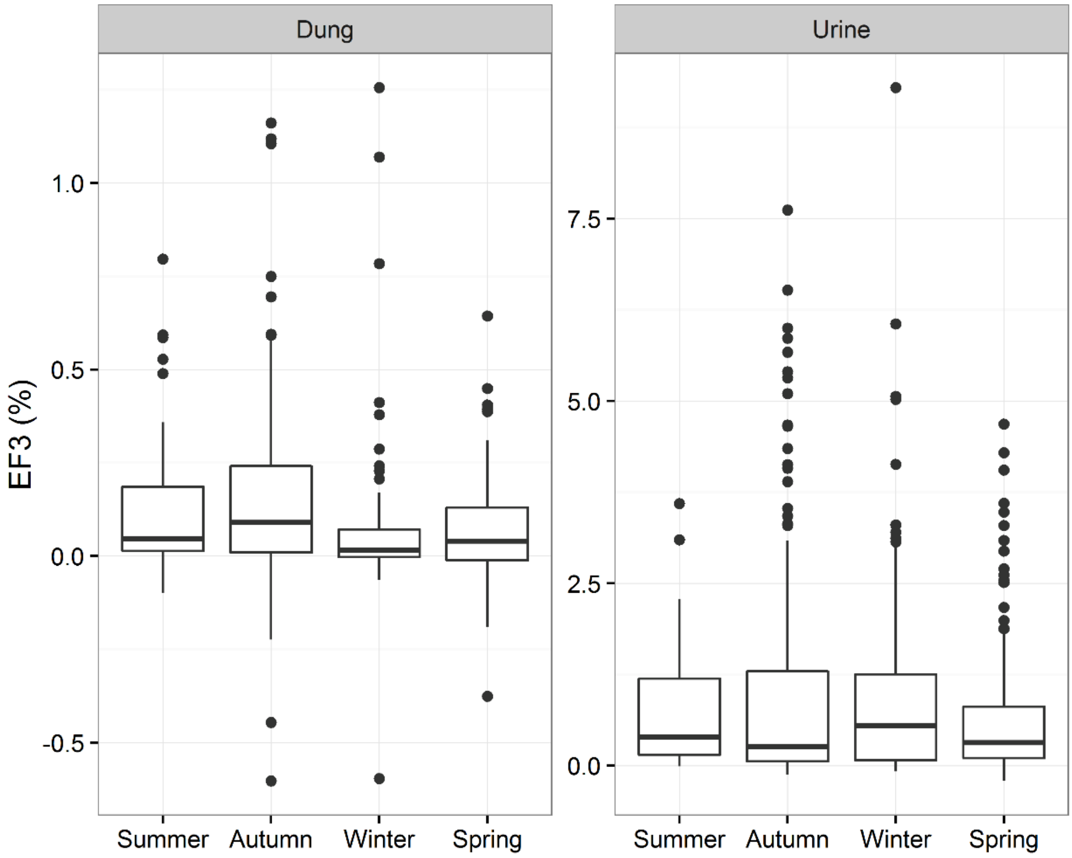

Fig. 1: Boxplot of seasonal EF_3 values for Dung and Urine data. The boxes show the 25th, 50th and 75th percentile, the whiskers show the 5th and 95th percentiles, the filled circles show outliers and the thick black line shows the mean.

Table 4: Effects of variables, N sources and their interactions on seasonal $\ln(EF_3)$.

Variable	Level of significance (P)
N excreta type	<0.001
Season (all Urine)	0.011
Season (all Dung)	0.011
Season (Dairy urine only)	0.53
Season (Beef urine only)	0.10
Season (Sheep urine only)	0.20
Season (Dairy dung only)	<0.001
Season (Beef dung only)	0.12
Season (Sheep dung only)	0.62
All analysis below includes N excreta type and Season as fixed terms	
N excreta type x Season	0.146
Drainage class	0.320
Drainage class x Season	0.050
Drainage class x N excreta type	0.005

Drainage class x Season x N excreta type	0.059
Topography	<0.001
Topography x N excreta type; Topography x Season	<0.001
Topography x Season x N excreta type	0.219
Region	0.015
Region x N excreta type; Region x Season	<0.001
Region x Season x N excreta type	<0.001
Relative rainfall	0.039
Relative rainfall x N excreta type; Relative rainfall x Season	0.046
Relative rainfall x Season x N excreta type	0.350

Table 5: Seasonal EF_3 values (%) for Urine and Dung (Mean; 95% confidence interval).

Excreta type	Season	Mean	Lower	Upper
Urine	Summer	1.00	0.69	1.45
	Autumn	0.87	0.56	1.29
	Winter	1.10	0.78	1.55
	Spring	0.40	0.18	0.73
Dung	Summer	0.23	-0.01	0.49
	Autumn	0.10	-0.09	0.38
	Winter	0.26	0.04	0.56
	Spring	-0.18	-0.33	0.03

We separated excreta type into the three livestock classes (beef, dairy and sheep) to determine whether season influenced EF for each of the class by excreta type combinations. The livestock class by excreta type results are presented and discussed below.

Urine

There was a non-significant seasonal effect on dairy urine EF_3 ($P = 0.53$; Fig. 2), beef urine ($P = 0.10$; Fig. 3) and sheep urine EF_3 ($P = 0.53$; Fig. 4). This was in spite of a significant seasonal effect on pooled urine EF_3 values ($P = 0.011$), as noted above. The lack of a seasonal effect on urine EF_3 at the livestock class scale was due to the disaggregation of the pooled urine EF_3 data into three classes creating relatively small sample sizes for each class leading to larger standard errors associated with seasonal mean EF_3 values. It is also important to note that there were fewer summer urine EF_3 values for each livestock class, with no summer data for sheep urine, illustrating the value of pooling the livestock classes for analysis of EF_3 variability across seasons.

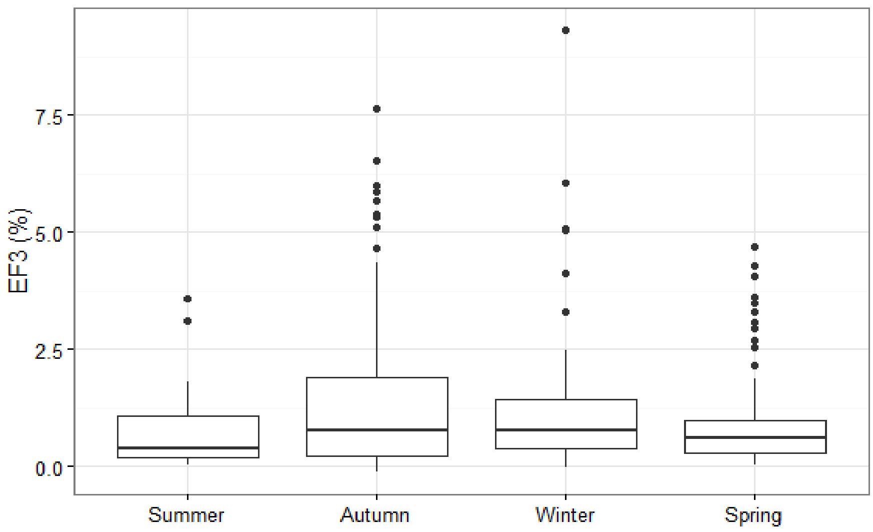

Fig. 2: Boxplot of seasonal variation in dairy urine EF_3. Refer to Fig. 1 for interpretation of boxplots.

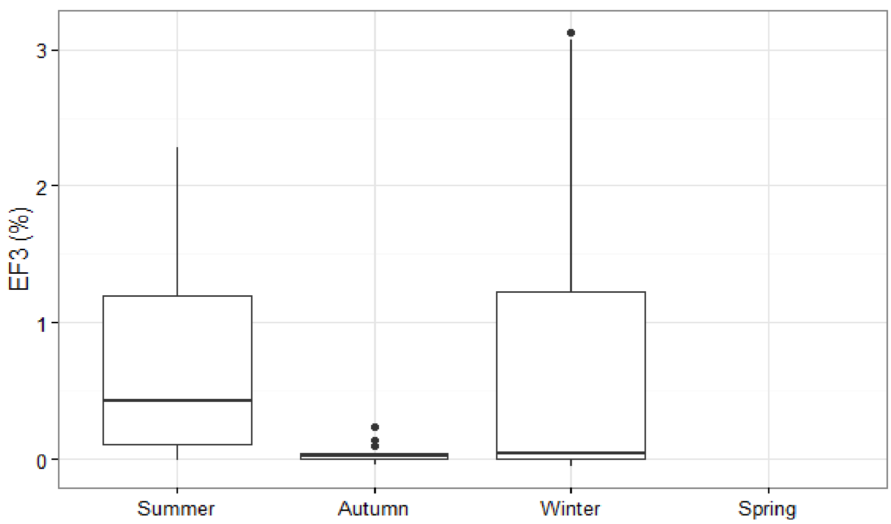

Fig. 3: Boxplot of seasonal variation in beef urine EF_3. Refer to Fig. 1 for interpretation of boxplots.

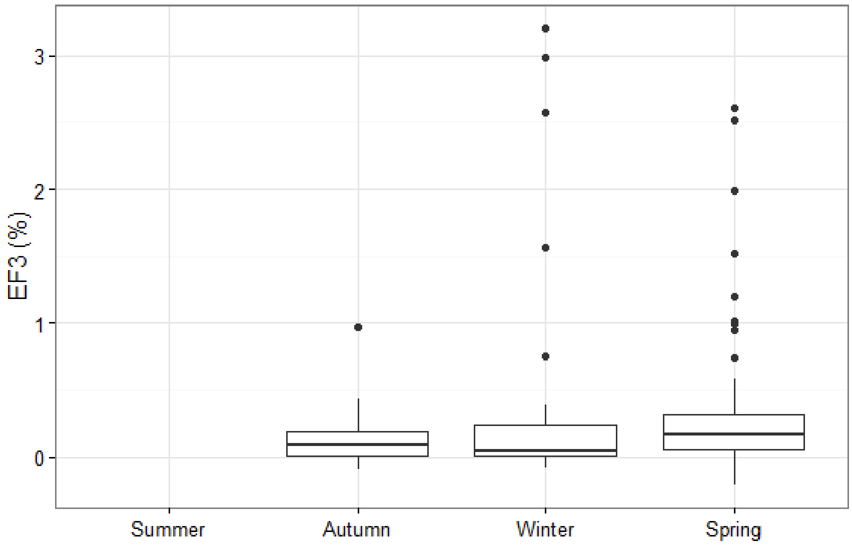

Fig. 4: Boxplot of seasonal variation in sheep urine EF_3. Refer to Fig. 1 for interpretation of boxplots.

Dung

While the number of EF_3 values for dairy dung was less than for dairy urine, at 110 compared to 411, respectively, there was a more even spread of values across seasons (Table 3). The raw data indicated seasonal differences in dairy dung EF_3 values (Fig. 5); this was supported by the statistical analysis which showed a significant seasonal effect on dairy dung EF_3 values ($P < 0.001$; Table 6). Autumn produced the highest mean value of 0.53% compared to 0.17% for summer and spring, while winter produced the lowest EF_3 of 0.09%. In contrast, there was no significant effect of season on beef dung EF_3 ($P = 0.12$), with mean values ranging from 0.00 to 0.12% (Fig. 6). There have been no summer studies measuring EF_3 for sheep dung, therefore, as for sheep urine, we cannot determine whether summer EF_3 for this N source differs from other seasons (Fig. 7). For the remaining three seasons there was no significant difference ($P = 0.62$). As for urine EF_3, these results illustrate the value of analysing the pooled livestock class data.

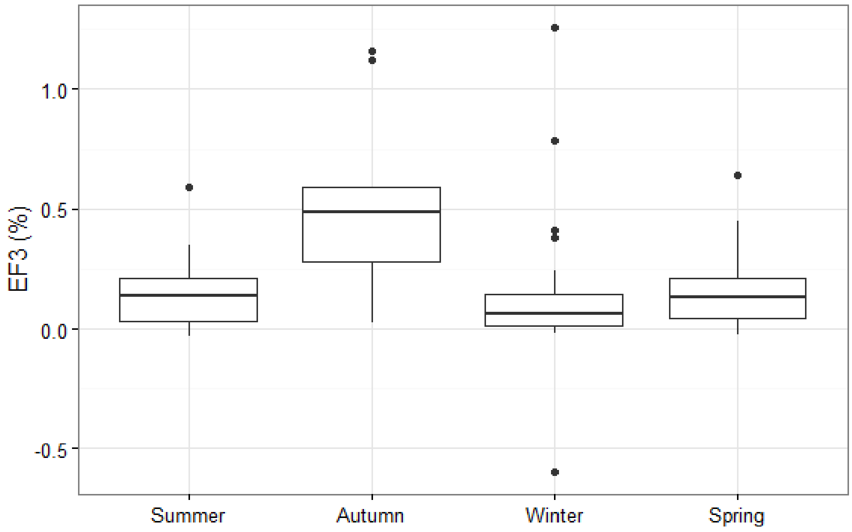

Fig. 5: Boxplot of seasonal variation in dairy dung EF_3. Refer to Fig. 1 for interpretation of boxplots.

Table 6: Seasonal EF_3 values (%) for dairy dung (Mean; 95% confidence interval).

Season	Mean	Lower	Upper
Summer	0.17	-0.09	0.55
Autumn	0.53	0.18	1.05
Winter	0.09	-0.15	0.44
Spring	0.17	-0.09	0.54

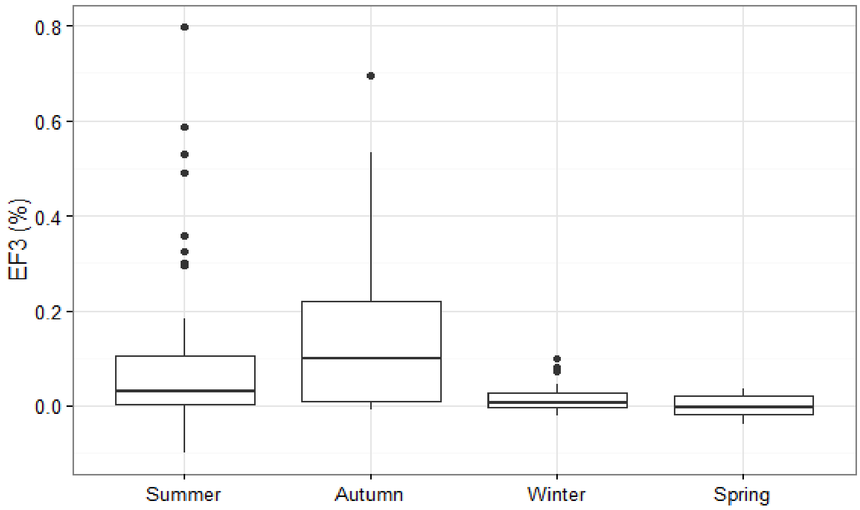

Fig. 6: Boxplot of seasonal variation in beef dung EF_3. Refer to Fig. 1 for interpretation of boxplots.

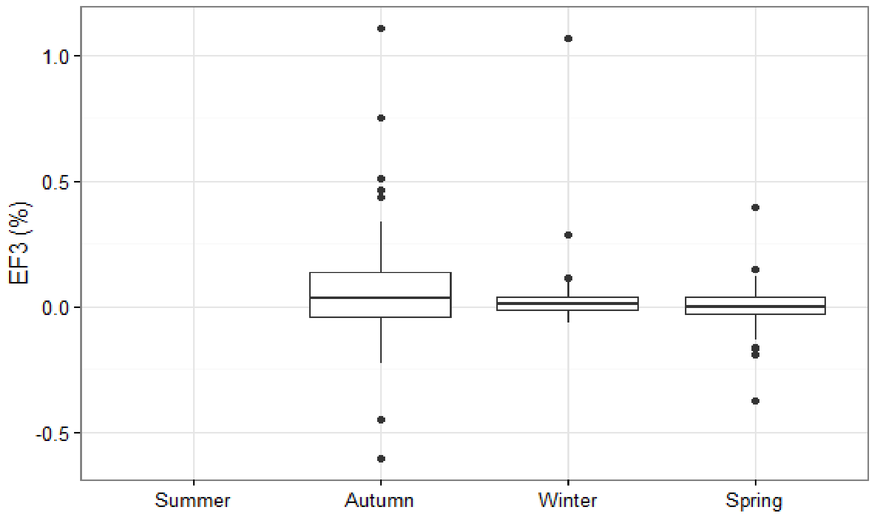

Fig. 7: Boxplot of seasonal variation in sheep dung EF_3. Refer to Fig. 1 for interpretation of boxplots.

4.3.3 Influence of key variables on seasonal EF_3

For all remaining analyses, both N excreta type and season were fitted as fixed effects. The rationale for this is the current disaggregation of EF_3 values into dung and urine within the national N_2O inventory model, while the focus of this review is on the difference between summer and other seasonal EF_3 values and how key variables influence seasonal EF_3. In addition, we also explored the effect of the key variables on the seasonal variation of EF_3 for dairy urine deposited on lowland pasture, as this particular N source and topography class had the largest number of EF_3 values (325 replicate-level values). The results were very similar to those for the pooled excreta data and have therefore not been included.

Soil drainage class

There was a significant interaction between drainage class and season ($P = 0.050$) and between drainage class and N excreta type ($P = 0.005$). As noted in our earlier analysis of key drivers of EF_3 (van der Weerden et al. 2014), it is likely that drainage class *per se* is not a driver of EF_3, but is likely to be an interaction of drainage class, rainfall and evapotranspiration (ET) encountered during the field trial. Freely drained soils produced the highest urine and dung EF_3 values in summer, whereas poorly drained soils produced the lowest urine EF_3 (Figure 8; Table 7). For dung on poorly drained soils, mean spring EF_3 values were negative, at -0.33% (Table 7). These results are influenced by the limited number of values, as all the poorly drained summer trials with dung were located at a single site (Ballantrae, in Hawkes Bay), with the free drained sites spread across 3 other regions (Waikato, Manawatu and Otago). An earlier analysis of negative fluxes showed that there was a large number of negative EF_3 values for dung from Ballantrae, which appeared to be related to dry soil conditions, warm temperatures and low soil nitrate levels (Clough et al. 2011). When data was averaged across seasons, freely drained soils produced higher urine and dung EF_3 values (0.90% and 0.23%, respectively) compared to poorly drained soils (0.60% and 0.05%, respectively). These differences appeared to be greatest for hill country EF_3 data, where poorly drained soils at Ballantrae frequently produced lower EF_3 values than the freely drained soils at other locations across New Zealand. The reason(s) for this difference are unclear, however it may be due to increased run-off from poorly drained soils reducing the soil water content and thereby lower denitrification activity and/or generally lower soil microbial activity at the Ballantrae station compared to other hill country soil. Soil drainage class had a minor effect on EF_3 values measured at lowland sites, probably due to the interaction of drainage class, rainfall and evapotranspiration (ET) encountered during field trials, as noted earlier.

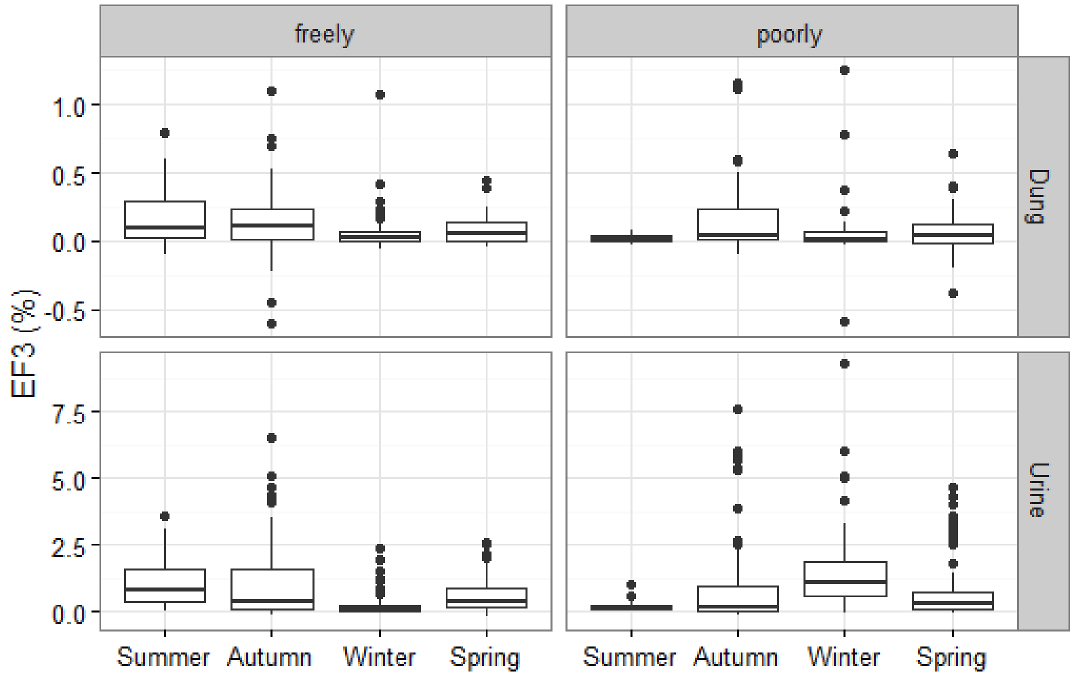

Fig. 8: Boxplot of influence of drainage on seasonal EF_3 values for dung and urine. Refer to Fig. 1 for interpretation of boxplots.

Table 7: Influence of soil drainage class on seasonal EF_3 values (%) for urine and dung (Mean; 95% confidence interval).

Drainage Class	Excreta type	Season	Mean	Lower	Upper
Freely	Urine	Summer	1.56	1.08	2.25
		Autumn	0.96	0.59	1.49
		Winter	0.74	0.40	1.23
		Spring	0.36	0.08	0.76
	Dung	Summer	0.44	0.15	0.87
		Autumn	0.38	0.10	0.80
		Winter	0.23	-0.02	0.60
		Spring	-0.16	-0.35	0.12
Poorly	Urine	Summer	0.06	-0.18	0.40
		Autumn	0.66	0.33	1.12
		Winter	1.25	0.83	1.85
		Spring	0.43	0.14	0.84
	Dung	Summer	0.01	-0.22	0.37
		Autumn	0.36	0.09	0.77
		Winter	0.17	-0.08	0.53
		Spring	-0.33	-0.49	-0.10

Topography

Topography had a highly significant effect on EF_3 ($P < 0.001$), with EF_3 values for both urine and dung generally decreasing in the order of lowland, hill country low slopes, hill country medium slopes and hill country steep slopes (Fig. 9; Table 8). There was also a highly significant interaction between topography and N excreta type and also topography and season ($P < 0.001$). This is illustrated by examining the dung EF_3 values in Table 8, where autumn produced the highest mean for lowland and hill country medium slopes whereas summer produced the highest mean values for low slopes on hill country. However, it is important to note that there are missing values for some of the topography x excreta type x season combinations. Luo et al. (2013) suggested that differences in soil fertility and microbial activity may drive the differences in N_2O emissions between slope classes.

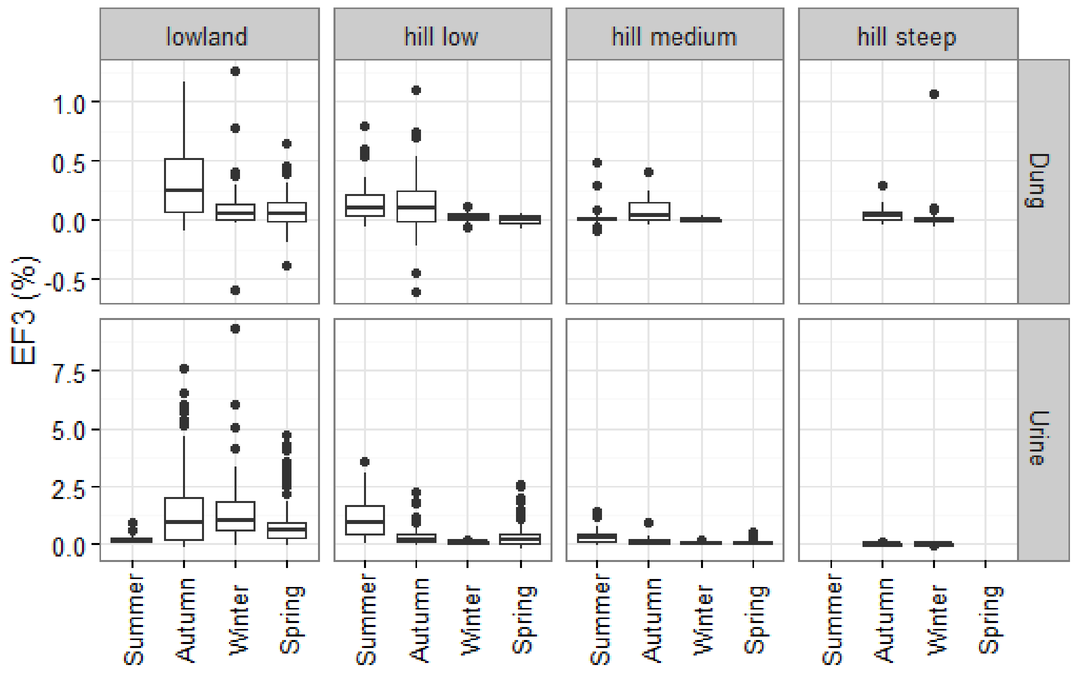

Fig. 9: Boxplot of influence of Topography on Seasonal EF_3 values for Dung and Urine. Refer to Fig. 1 for interpretation of boxplots.

Table 8: Influence of Topography on Seasonal EF_3 values (%) for Urine and Dung (Mean; 95% confidence interval).

Topography	Excreta type	Season	Mean	Lower	Upper
Lowland	Urine	Summer	0.44	0.09	0.95
		Autumn	1.28	0.75	2.01
		Winter	1.40	0.85	2.19
		Spring	0.82	0.41	1.41
	Dung	Summer			
		Autumn	0.40	0.10	0.83
		Winter	0.48	0.15	0.94
		Spring	0.13	-0.11	0.48
Hill country – Low slope	Urine	Summer	0.64	0.27	1.18
		Autumn	0.36	0.06	0.78
		Winter	0.32	0.02	0.76
		Spring	0.27	-0.01	0.66
	Dung	Summer	0.42	0.10	0.87
		Autumn	0.18	-0.08	0.55
		Winter	0.15	-0.11	0.52
		Spring	0.11	-0.13	0.44
Hill country – Medium slope	Urine	Summer	0.25	-0.03	0.65
		Autumn	0.17	-0.08	0.54
		Winter	0.25	-0.04	0.66
		Spring	0.02	-0.20	0.35

	Dung	Summer	0.09	-0.15	0.43
		Autumn	0.02	-0.20	0.34
		Winter	0.09	-0.15	0.44
		Spring			
Hill country – Steep slope	Urine	Summer			
		Autumn	0.00	-0.22	0.31
		Winter	0.02	-0.20	0.36
		Spring			
	Dung	Summer			
		Autumn	0.05	-0.19	0.38
		Winter	0.08	-0.16	0.43
		Spring			

Region

Region showed a highly significant effect on EF_3 ($P = 0.015$). Interactions between region and N excreta type and also region and season were also found to be highly significant ($P < 0.001$). Interestingly, a three way interaction between region, season and N excreta type was also highly significant ($P < 0.001$).

As noted in our earlier assessment of variables influencing EF_3 (van der Weerden et al. 2014), region may account for the effect of temperature and soil moisture variation on EF_3. Soil moisture content effects are strongly influenced by rainfall and the soil type at the location of the individual trials within a single region. Thus, it can be difficult to determine the specific drivers behind regional variation in annual and seasonal EF_3 values. However, in the case of Hawkes Bay, the relatively low mean EF_3 values for both urine and dung (Fig. 10) came from a single hill country site (Ballantrae), where emissions have historically been low (e.g. Luo et al. 2013). In contrast, Manawatu and Canterbury field trials have produced relatively high mean EF_3 values for both urine and dung. It is important to note that there is an absence of summer field trials in Canterbury. This is a significant gap in current knowledge considering the increasing area of pasture under irrigation in this region: this is further discussed later (section 4.3.4).

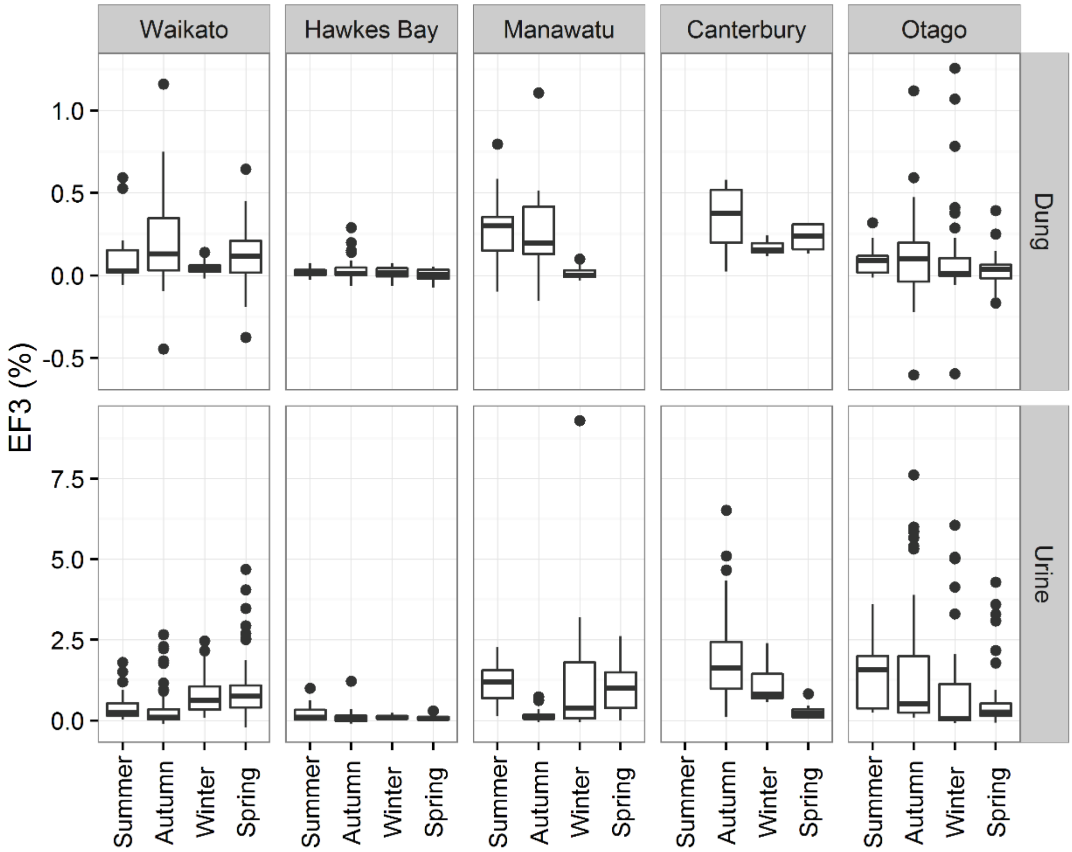

Fig. 10: Boxplot of influence of Region on Seasonal EF_3 values for Dung and Urine. Refer to Fig. 1 for interpretation of boxplots.

Relative rainfall

There was a significant interaction between relative rainfall (i.e. the ratio between 'actual rainfall over the first 30 days of the trial' and 'long-term average rainfall for the same period') and N excreta type and also relative rainfall and season (0.005). The influence of relative rainfall on dung EF_3 values appears to be minimal. In contrast, relative rainfall influenced seasonal urine EF_3; for example, mean values were highest from field trials with a high relative rainfall in spring and autumn whereas in summer and winter, a low relative rainfall produced the highest mean urine EF_3 values (Fig. 11). While this analysis includes other variables as random effects, it does suggest that our changing climate will also affect N_2O emissions. For example, as New Zealand moves towards drier winters in eastern regions and more summer droughts in the North Island and eastern regions of the South Island due to climate change (SLUA, 2013), associated N_2O emissions may increase. However, as noted earlier, caution is advised when interpreting this data due to the influence of the other variables such as soil drainage on the reported results.

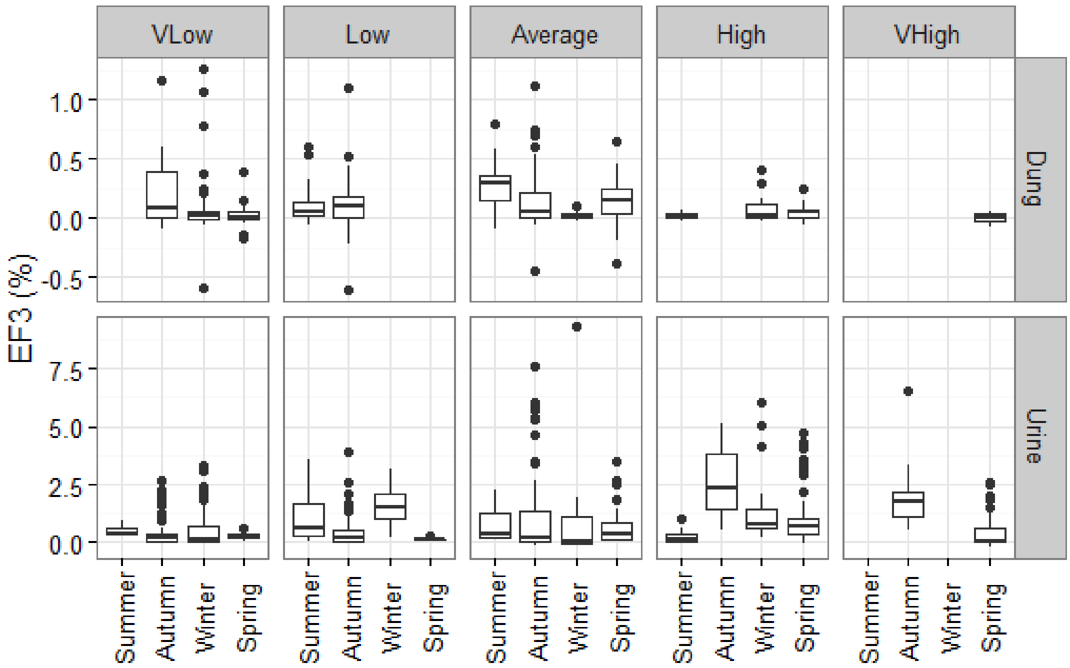

Fig. 11: Boxplot of influence of relative rainfall on seasonal EF_3 values for dung and urine. Refer to Fig. 1 for interpretation of boxplots.

4.3.4 Influence of irrigation on summer EF_3

To provide an assessment and discussion of the influence of irrigation on summer EF_3, we have included relevant information from a recently completed review for MPI on this topic (Thomas et al. 2016). The authors found that irrigation management is likely to have a large effect on urine EF_3. Overall, modelling and field trials indicate that where soils were maintained wet (frequently irrigated back to field capacity) emissions would be enhanced, and through less frequent irrigation and retaining greater soil moisture deficit these emissions can be reduced.

Thomas et al. (2016) also highlighted the potential over-estimation of emissions from freely drained soils in Canterbury and Otago; and under-estimation of emissions from poorly drained soils in these regions. Measurements from irrigated field trials suggested that urine EF_3 for freely drained soils is less than half the current New Zealand-specific value of 1%. Conversely, predicted and measured urine EF_3 from irrigated poorly drained soils (a single field site) were approximately 10 times larger than the freely drained soils, and larger than NZ's EF_3 value. Before considering disaggregating land by irrigation and/or soil drainage class a better understanding is required of the drivers of the effect of soil type on irrigation-affected EF_3 values.

While there was evidence that irrigated soils emit more N_2O, Thomas et al. (2016) recommended there is currently insufficient justification or supporting information for modifying or applying a new EF_3 value for irrigation in the inventory for the following reasons:

- The value(s) would be highly uncertain based on limited data.
- Based on current land use, the increase in inferred EF_3 appears to be small if irrigation is accounted for.
- Evidence of effects of irrigation on emissions is highly variable. This variability is likely to be affected by both soil type and the type of irrigation management. Studies on similar soils under similar climate regimes have reported either a strong or no response. More information is required to understand and quantify this variability.
- Emissions from freely drained soils, the dominant soil type receiving irrigation, appears to be much smaller than the NZ EF_3 value. This needs further investigation and needs to be addressed for dryland as well as irrigated soils.
- There are limited or no data for irrigation derived emission factors from dung and fertiliser.
- There is a lack of international data to support any revision of EF_3 from irrigated pasture. Most key information is from the few NZ studies.

This uncertainty in the value for EF_3 for irrigated land could be addressed in the future through some targeted field studies supported by modelling. Modelling approaches have been used overseas to derive emission factors for fertiliser under different environmental conditions.

4.3.5 Influence of key variables on seasonal EF_1

The updated dataset contained 196 replicate-level EF_1 values, of which only 17 were measured in summer. Our analysis showed a seasonal effect (P = 0.078), which may reflect the smaller dataset for urea fertiliser (196) compared to urine (679) and dung (356). Even so, the mean for winter (1.27%) was nearly 20 times larger than for summer (0.07%; Fig. 12 and Table 9). As for excreta EF_3, the high winter EF_1 values may be due to generally wetter soil conditions. However, in contrast to excreta, summer produced the lowest EF_1 values even though the generally warmer conditions could be expected to stimulate microbial activity, leading to increased N_2O emissions. The lower summer EF_1 values compared to urine EF_3 may relate to increased plant growth and therefore maximum plant N and water uptake, as well as improved N use efficiency at low N loadings (van der

Weerden et al. 2016b). Our dataset showed an average urea N load of 53 kg N/ha, in contrast the higher loads of 560 kg and 709 kg N/ha for urine and dung, respectively.

Approximately 65% of urea fertiliser is applied in spring (J. Morton, pers. comm. 2016), justifying the large number of studies (45%) conducted at this time of year. However, with increasing areas of pasture receiving irrigation, urea fertiliser use in summer months is also likely to be increasing. Our dataset does not include any studies on the effects of irrigation on urea EF_1 due to the limited amount of information available (Thomas et al. 2016).

Region had a significant seasonal effect on EF_1 ($P = 0.027$; Table 10), due to the high winter and spring values measured in the Manawatu compared to other regions (Fig. 13 & Table 11). None of the other remaining variables (drainage class, topography, relative rainfall) influenced seasonal EF_1 (Table 10). Results for these are shown below (Figs. 14- 16).

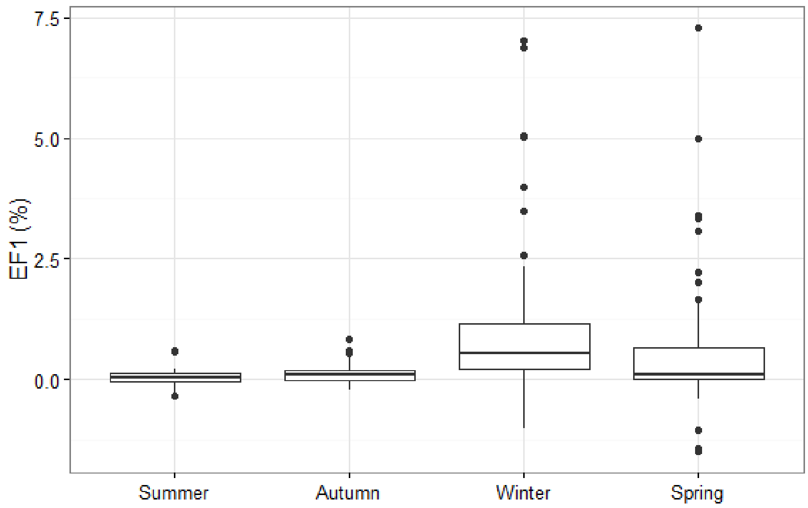

Fig. 12: Boxplot of influence of season on urea EF_1 values. Refer to Fig. 1 for interpretation of boxplots.

Table 9: Seasonal EF_1 values (%) for urea fertiliser (Mean; 95% confidence interval).

Season	Mean	Lower	Upper
Summer	0.07	-0.69	1.50
Autumn	0.18	-0.61	1.66
Winter	1.27	0.17	3.31
Spring	0.46	-0.42	2.08

Table 10: Effects of variables on seasonal ln(EF_1).

Variable	Level of significance (P)
Season	0.078
All analysis below include Season as fixed terms	
Region	0.027
Drainage class	0.990
Topography	0.320
Relative rainfall	0.140

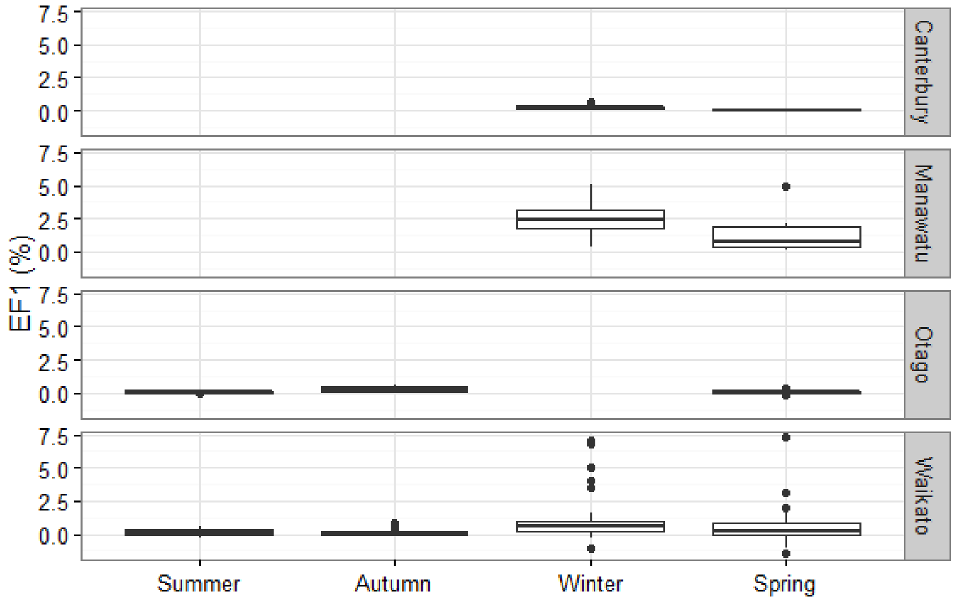

Fig. 13: Boxplot of influence of region on seasonal urea EF_1 values. Refer to Fig. 1 for interpretation of boxplots.

Table 11: Influence of region on seasonal EF_1 values (%) for urea fertiliser (Mean; 95% confidence interval).

Region	Season	Mean	Lower	Upper
Waikato	Summer	0.16	-0.61	1.54
	Autumn	0.18	-0.59	1.57
	Winter	1.17	0.12	3.11
	Spring	0.46	-0.39	2.01
Manawatu	Summer			
	Autumn			
	Winter	3.20	1.48	6.22
	Spring	1.93	0.60	4.47
Canterbury	Summer			
	Autumn			
	Winter	0.56	-0.34	2.22
	Spring	0.06	-0.67	1.37
Otago	Summer	-0.03	-0.75	1.35
	Autumn	0.16	-0.62	1.55
	Winter			
	Spring	0.16	-0.60	1.54

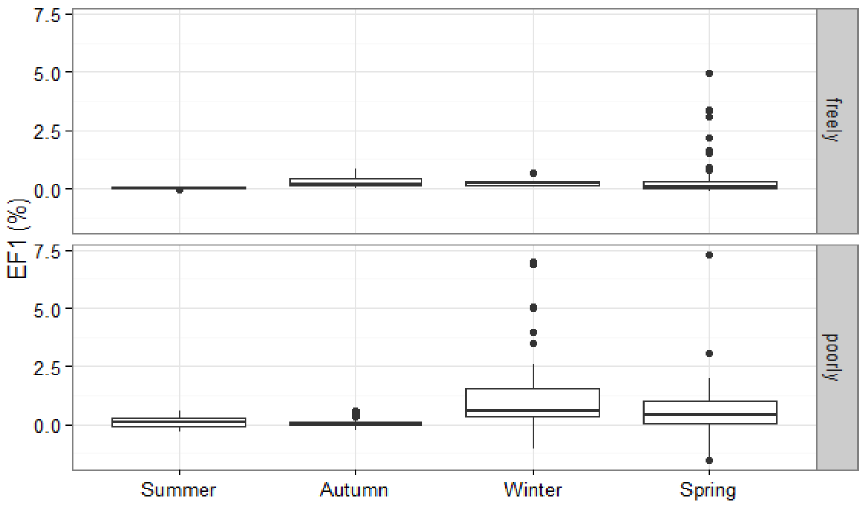

Fig. 14: Boxplot of influence of soil drainage class on seasonal urea EF_1 values. Refer to Fig. 1 for interpretation of boxplots.

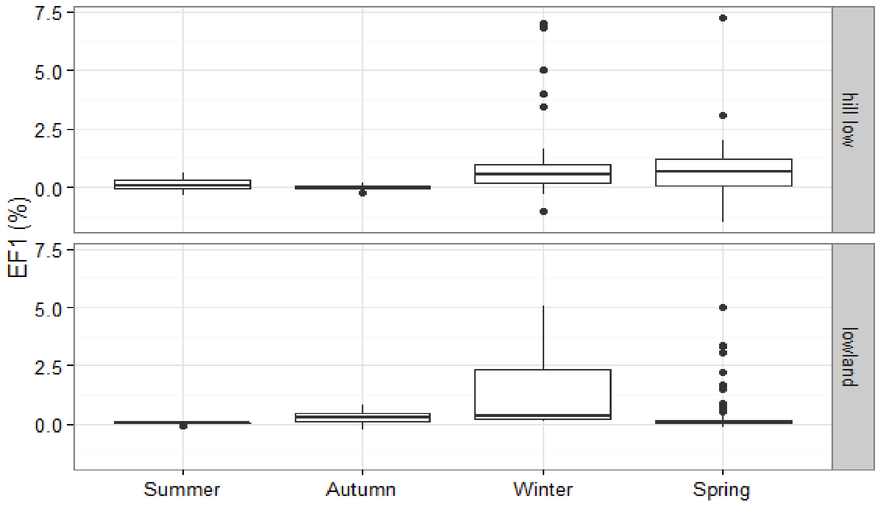

Fig. 15: Boxplot of influence of topography on seasonal urea EF_1 values. Refer to Fig. 1 for interpretation of boxplots.

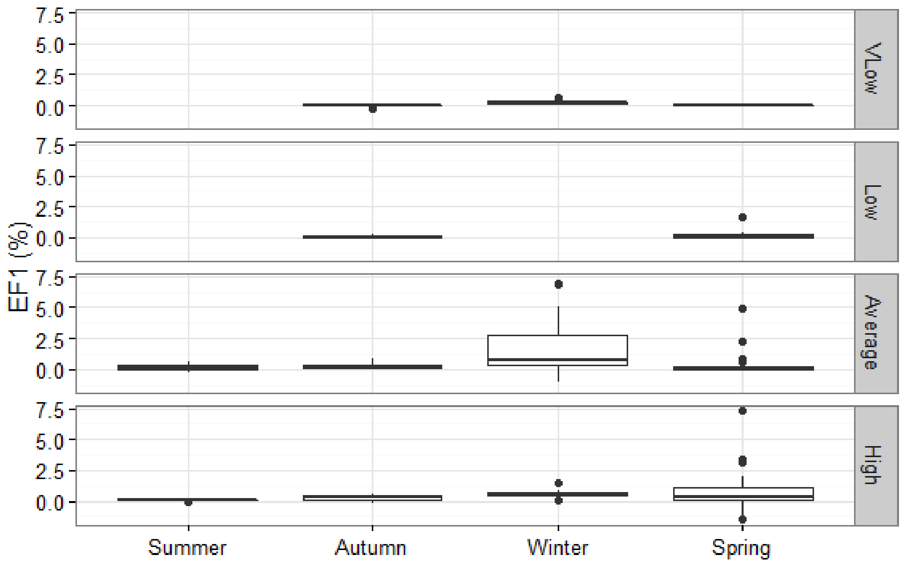

Fig. 16: Boxplot of influence of relative rainfall on seasonal urea EF_1 values. Refer to Fig. 1 for interpretation of boxplots.

4.4 Summary of Key Points

From the statistical analysis, the following key points were made.

- The number of summer EF_3 values represented only 13% of the total EF_3 database; summer EF_1 values were only 9% of the total EF_1 database.

- For urine, the overall mean summer EF_3 value was 1.00%, which was between the values for winter (1.10%) and autumn (0.87%).The spring value was lowest, at 0.40%.
- For dung, summer and winter had the highest mean EF_3 value (0.23 and 0.26%, respectively), while the autumn was 0.10% and spring was lowest, at -0.18%.
- Seasonality has a significant effect on EF_3, with winter producing the highest EF_3 values, probably due to wet soils stimulating N_2O emissions. For excreta, summer produced the second highest EF_3 values, possibly due to N_2O production stimulated by warm conditions.
- At the livestock class level, seasonality has a significant effect on dairy dung EF_3, with a mean summer and spring value of 0.17% lying between the higher autumn value of 0.53% and lower winter value of 0.09%.
- However, seasonality did not significantly affect the remaining dairy cattle, beef and sheep urine and dung EF_3 combinations.
- There was a significant interaction between the effect of soil drainage class and season on EF_3, with freely drained soils producing the highest summer EF_3 values and poorly drained soils generally producing low summer EF_3 values.
- Topography, region and relative rainfall all have a significant influence on seasonal EF_3 values. Unfortunately, the unbalanced nature of the dataset makes it difficult to interpret of the effect of these variables on seasonal EF_3.
- There is evidence that irrigated soils emits more N_2O, however the magnitude of its effect is variable. Limited or no data makes it difficult to provide ‘irrigation’ EF values for urine, dung and urea fertiliser.
- There was a non-significant seasonal effect on $EF_{1.}$ However, the numerical differences in EF_1 between seasons was large, with the overall mean summer value of 0.07%, which was the lowest of all seasons, being nearly 20 times lower than the winter value of 1.27%. The low summer EF_1 value contrasts with the high EF_3 values for the same season. This may have been influenced by N load, which averaged 53 kg N/ha for urea. Low N load may lead to increased N use efficiency by actively growing pasture, and therefore lower N_2O emissions, compared to high excreta N loads (average of 612 kg N/ha).
- Region has a significant effect on seasonal EF_1 values, with high values measured in winter and spring in the Manawatu compared to other regions.
- All remaining variables (drainage class, topography and relative rainfall) did not influence seasonal urea EF_1 values.

5. Uncertainty analysis of summer EF_3

5.1 Modelling methodology

For this study, there were 1,035 replicate-level EF_3 values including 679 for sheep and cattle urine and 356 for dung (Table 12). For NZ's agricultural soils N_2O emissions inventory, based on a study published by Kelliher et al. (2014a), the mean EFs and 95% CIs had been calculated by a meta-analysis which included 801 EF_3 values with 529 for urine and 272 for dung. While this study had 150 more urine replicates and 84 more dung replicates, the two sets of data had very similar seasonal distributions. Notably, the two sets had almost identical numbers of urine and dung replicates for the spring and summer seasons. In contrast, this study had 89 more urine replicates in the autumn season and 40 more dung replicates, while in winter, the corresponding numbers were 52 and 40.

Table 12 Number of replicate-level EF_3 values for each season for this study and for an earlier EF meta-analysis published by Kelliher et al. (2014a).

N source	Autumn	Winter	Spring	Summer	Total
Kelliher et al. (2014)					
Urine	176 (33%)	97 (18%)	184 (35%)	72 (14%)	529
Dung	64 (24%)	72 (26%)	76 (28%)	60 (22%)	272
This study					
Urine	265 (39%)	149 (22%)	188 (28%)	77 (11%)	679
Dung	104 (29%)	112 (31%)	80 (23%)	60 (17%)	356

For this study and that done by Kelliher et al. (2014a), we estimated weighted mean EF_3 values for urine and dung. The weighting factors were determined by the annual N_{ex} data calculated for NZ's inventory during the year 2012. For this study, the weighted mean EF_3 was 0.59 ± 0.48% (± 95% confidence interval, 95% CI). For Kelliher et al. (2014a), by the same calculation methodology, the corresponding mean EF_3 was 0.65 ± 0.35%. Thus, by the availability of additional data since the publication of Kelliher et al. (2014a), the mean EF_3 has reduced slightly but not significantly (P > 0.05) and the variability increased substantially. For this study, the 95% CI was 83% of the mean, while for Kelliher et al. (2014a), this percentage would be 54%. These different results from the two studies were interpreted to indicate this study's data set was larger and it evidently included a greater variability of "conditions" which led to the greater variability of EF_3. Put another way, Kelliher et al. (2014a) evidently under-estimated the true variability of EF_3. For Kelliher et al. (2014a), 43% of the urine replicate-level EF_3 values came from hill country field trials, though only 11% from medium slope positions and there were no data from steep slope positions. For dung, their corresponding percentages were 47 and 7%. For this study with 234 more urine and dung replicate-level EF_3 values, 43% of the urine data came from hill country field trials as well as 61% of the dung data.

5.2 The effect of EF_3 variability on the uncertainty of NZ's N_2O emissions inventory for grazing sheep and cattle

For our uncertainty assessment, we will represent NZ's inventory of agricultural soils N_2O emissions (E_{N2O}) as the product of two variables. The first variable, $N_{ex,}$ is the nitrogen (N) deposited onto soils as excreta by grazing sheep and cattle. The second variable is a weighted mean EF_3 values for urine and dung. As described in the previous section, the weighting factor was determined by proportions of the total N_{ex} attributed to the urine and dung of sheep and cattle. This simplified representation of the inventory can be written as an equation

$$E_{N2O} = N_{ex} * EF_3 \qquad (1)$$

The uncertainty of E_{N2O} will depend on the variability of N_{ex} and EF_3. For each variable, the variability can be quantified by the standard deviation (SD). To account for the number of samples (n), the variability can be quantified by the standard error (SE = $SD/n^{0.5}$). To estimate the uncertainty of a variable, we will calculate the fractional SE by a ratio of the SE and mean (FSE = SE/mean). For 95% confidence, the FSE will firstly be multiplied by two and then by 100 for expression as a percentage.

For N_{ex}, using expert judgement, the FSE was estimated to be 0.075 (Kelliher et al. 2016). As shown in the previous section, the FSE for EF_3 was 0.42 from this study, keeping in mind the FSE is half the 95% CI (for this study, the 95% CI for EF3 was 83% of the mean). Alternatively, the FSE for EF_3 would be 0.27, so smaller according to Kelliher et al. (2014a).

Using the FSE nomenclature, we can estimate the inventory's uncertainty using the Taylor series approximation for a product of variables which may be written

$$FSE(E_{N2O}) = \{FSE(N_{ex})^2 + FSE(EF_3)^2 + 2\, \rho\, FSE(N_{ex})\, FSE(EF_3)\}^{0.5} \qquad (2)$$

where term ρ is the correlation of N_{ex} and EF_3 (Mood et al. 1974). Kelliher et al. (2016) developed a complete analytical equation to estimate $FSE(E_{N2O})$. We found the results from their equation and equation (2) differed by less than 2% when $FSE(N_{ex}) = 0.075$, $FSE(EF_3) = 0.42$ or 0.27 and $\rho = 0 – 1$ (data not shown).

When N_{ex} and EF_3 are not correlated, $\rho \rightarrow 0$ and equation (2) becomes

$$FSE(E_{N2O}) = \{FSE(N_{ex})^2 + FSE(EF_3)^2\}^{0.5} \qquad (3)$$

For this situation, equation (3) shows the uncertainty or error in E_{N2O} can be estimated by a root sum square of the errors in N_{ex} and EF_3. As stated, in equation (3), N_{ex} will be an annual sum and EF_3 will be a weighted annual mean. To use equation (3) to estimate the uncertainty of a seasonal inventory, estimates of $FSE(N_{ex})$ and $FSE(EF_3)$ will be needed for the four seasons.

We first assessed the inventory's uncertainty on an annual basis using equation (3), and assumed N_{ex} and EF_3 are not correlated. For $FSE(N_{ex}) = 0.15$ and $FSE(EF_3) = 0.27$ from Kelliher et al. (2014a), the estimated 95% CI of E_{N2O} was ± 62%. For $FSE(N_{ex}) = 0.15$ and $FSE(EF_3) = 0.42$ from this study, the estimated 95% CI of E_{N2O} was ± 89%. By these results, we have found the inventory's uncertainty to be largely determined by $FSE(EF_3)$ because it is so much larger than $FSE(N_{ex})$. Moreover, as stated, we found Kelliher et al. (2014a) under-estimated the true variability of EF_3.

We then assessed the inventory's uncertainty on a seasonal basis using equation (3), again assuming the seasonal estimates of N_{ex} and EF_3 are not correlated. For each of the four seasons, in the absence of contrary information, we will assume $FSE(N_{ex}) = 0.15$. From this study, $FSE(EF_3)$ was 0.30 for summer, 0.48 for autumn, 0.27 for winter and 0.46 for spring. On average, the seasonal $FSE(EF_3)$ was 0.38 which was similar to the annual or overall value of 0.42 from this study. To interpret this result, we recall that SD is an estimate of the variability and $SE = SD/n^{0.5}$. Though term n for each of the four seasonal estimates of $FSE(EF_3)$ was reduced compared to the (overall) annual estimate, evidently and not surprisingly, the SD (variability) of EF_3 within a season was less than throughout the year. For the seasonal $FSE(N_{ex})$ and $FSE(EF_3)$ data, the estimated 95% CI of E_{N2O} was ± 158%. As stated, for the annual $FSE(N_{ex})$ and $FSE(EF_3)$ data from this study and using equation (3), the estimated 95% CI of E_{N2O} had been ± 89%.

By these results, we found the inventory's uncertainty increased by nearly a factor of two when the basis for the (same) calculations changed from annual to seasonal. We attributed a much larger estimated 95% CI of E_{N2O} for the seasonal calculations to the arithmetic of a root mean square sum of four errors (in EF_3 and N_{ex}) compared to one. Seasonal EF values increase the uncertainty in the estimate of the N_2O inventory, however the accuracy of the estimate is improved when compared to a single annual EF value.

5.3 Summary of Key Points

From the uncertainty analysis, the following key points were made.

- The uncertainty in EF_3 was quantified using the fractional standard error (FSE), which is the SE expressed as a fraction of the mean value (i.e. a dimensionless value).
- An analysis of our data showed, for annual EF_3, the FSE was 0.42. On a seasonal basis, the FSE for EF_3 was 0.30 for summer, 0.48 for autumn, 0.27 for winter and 0.46 for spring.
- The uncertainty in the N_2O inventory, or 95% confidence interval (CI), is dependent on the uncertainty of both N_{ex} and EF_3. Using the FSE values for annual and seasonal EF_3, and appropriate FSE values for N_{ex}, the 95% CIs in the N_2O inventory for sheep and cattle excreta deposited onto soils based on annual or seasonal EF values were estimated.
- When a single annual EF_3 value was used, the estimated 95% CI of the N_2O inventory was ± 89%.
- However, when seasonal EF_3 values were used, the 95% CI increased by nearly a factor of two to ± 158%.
- As expected, using seasonal EF_3 values increases the uncertainty, however the accuracy of the national inventory will be improved.

6. Modelling the effect of a Summer EF_3 on the National N_2O Inventory

6.1 Modelling methodology

A spreadsheet-based inventory model for calculating direct N_2O emissions from grazing livestock was used to assess the effect of monthly and seasonal EF_3 values on calculated N_2O emissions. A similar approach was adopted for the recent assessment of whether irrigation should be incorporated into the national inventory (Thomas et al. 2016). The current assessment was restricted to N_2O emissions from excreta deposition and did not include other N sources (e.g. fertiliser, crop residues). Furthermore, indirect emissions were excluded from this assessment. Results are reported as total direct N_2O emissions from each grazing livestock class (dairy cattle, beef cattle, sheep and deer), and as a percentage change to these totals when adopting either monthly or seasonal EF_3 values for the different livestock types.

Dairy, beef, sheep and deer N_{ex} data from the 2012 inventory was used (MPI, 2014), based on the Agricultural Census and disaggregated at a monthly scale (see Appendix A for data). Beef, sheep and deer dung and urine were disaggregated by slope class (low, medium and steep slopes) using regional Sheep and Beef Farm Survey data (Saggar et al. 2015). Slope classes were the same as those defined in the data analysis i.e. low (< 12 °), medium (12 – 24 °) and steep (>24 °). The distribution of excreta between dung and urine was based on the Tier 2 inventory model and is split evenly across the year as 73% urine and 27% dung for dairy excreta, and 66% urine and 34% dung for sheep, beef and deer excreta.

6.2 Source of EF_3 values

We used three different sources of EF_3 for estimating national inventory N_2O emissions for livestock grazing; the first were annual EF_3 values for each livestock class, thereby representing 'baseline' conditions; the second were seasonal EF_3 values based on a modelling approach described in an earlier study (van der Weerden et al. 2014). And the third, also seasonal EF_3, were derived from the statistical analysis of the current dataset. Below we provide further detail for each source.

6.2.1 Annual EF_3

Annual average EF_3 values were based on the current (dairy) and proposed (sheep and beef) inventory approaches. For annual dairy EF_3 values, 1% and 0.25% for urine and dung were employed (Ministry for the Environment, 2016). For annual beef, deer and sheep, proposed EF_3 values for different slope classes (low, medium and steep) were employed based on values reported by Kelliher et al. (2014) and Saggar et al. (2015). Saggar et al. (2015) suggested medium and steep slopes could adopt the same EF_3 value. Furthermore, in the absence of data for deer EF_3, we followed the suggestion by Saggar et al. (2015) to use beef EF_3 values for this livestock class.

6.2.2 Seasonal EF_3 based on soil water model and temperature correction

We derived our first series of seasonal EF_3 values for dairy urine by estimating monthly urine EF_3 values based on soil water content and corrected for soil temperature effects, where it was assumed the rate of biological processes would increase 3-fold for every 10 °C increase i.e. $Q_{10} = 3$ (Fig. 17a, sourced from Table 24 in van der Weerden et al. 2014). We will refer to these seasonal EF_3 values as $EF_{3\ SWC}$ to indicate they were derived from modelling of soil water content. We adjusted the values by 3% to ensure the annual average of the monthly values was equivalent to the annual EF_3 of 1% currently used in the inventory (Table 13). The monthly $EF_{3\ SWC}$ values were then averaged across appropriate months to calculate seasonal $EF_{3\ SWC}$ (Table 13). The earlier modelling work of van der Weerden et al. (2014) did not include disaggregation of annual dung EF_3 into monthly or seasonal values, therefore we assumed dung EF_3 remained constant overtime i.e. annual dung EF_3 were employed.

For monthly beef, deer and sheep urine EF_3 values, we disaggregated the annual values of Saggar et al. (2015) by month (Fig. 17b & c) using the modelled monthly percentage variation in dairy urine EF_3, from Figure 17a. As for dairy, we ensured the annual average of the monthly values was equivalent to the annual EF_3 reported by Saggar et al. (2015). To calculate seasonal EF_3 values, monthly values were averaged across the appropriate months (Table 13). As for dairy, annual dung EF_3 were employed.

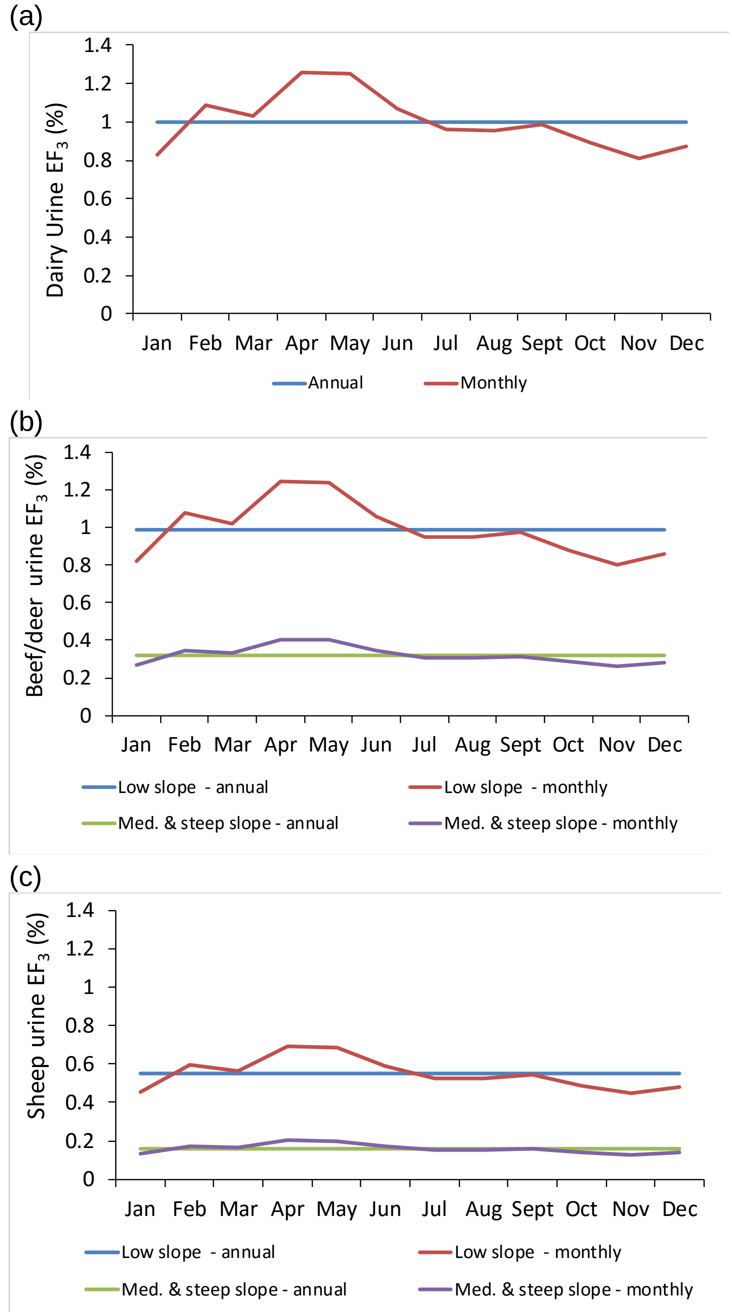

Fig. 17. Monthly and annual urine $EF_{3\ SWC}$ values used for scenario testing, for dairy (a), beef and deer (b) and sheep (c). See text for explanation of origin of monthly values.

Table 13: Estimated annual and seasonal EF_3 values (%) for dairy, beef/deer and sheep urine and dung employed in inventory modelling. Shaded cells depict estimates due to missing data – see text for details.

Source of EF_3/ Excreta type	Season	Dairy – lowland	Beef/deer – low slope	Beef/deer – medium & steep slope	Sheep – low slope	Sheep – medium & steep slope
Annual ('Baseline')						
Dung	Annual	0.25	0.21	0.06	0.11	0.11
Urine	Annual	1.00	0.99	0.32	0.55	0.16
Seasonal – $EF_{3\ SWC}$[A]						
Dung	Annual	0.25	0.21	0.06	0.11	0.11
Urine	Summer	0.93	0.92	0.30	0.51	0.15
	Autumn	1.18	1.17	0.38	0.65	0.19
	Winter	0.99	0.98	0.32	0.55	0.16
	Spring	0.90	0.89	0.29	0.49	0.14
	Annual[C]	*1.00*	*0.99*	*0.32*	*0.55*	*0.16*
Seasonal – $EF_{3\ DS}$[B]						
Dung	Summer	0.17	0.17	0.05	0.07	0.05
	Autumn	0.54	0.19	0.10	0.11	0.06
	Winter	0.10	0.04	0.01	-0.03	0.04
	Spring	0.17	0.00	0.05	0.05	0.05
	Annual[C]	*0.25*	*0.10*	*0.05*	*0.05*	*0.05*
Urine	Summer	0.30	1.06	0.35	0.16	0.07
	Autumn	1.43	1.43	0.04	1.38	0.10
	Winter	1.28	2.17	0.03	0.40	0.03
	Spring	1.06	1.06	0.14	0.64	0.09
	Annual[C]	*1.02*	*1.43*	*0.14*	*0.65*	*0.07*

[A] $EF_{3\ SWC}$: EF_3 modelled from soil water content and temperature (van der Weerden et al. 2014); [B] $EF_{3\ DS}$: EF_3 modelled from current dataset; [C] Annual values in italics are means of seasonal values, for comparing with annual values used for baseline calculations.

6.2.3 Seasonal EF_3 based on dataset modelling

We also modelled seasonal EF_3 values using the updated dataset: both urine and dung EF_3 values were derived (Table 13). We will refer to these seasonal EF_3 values as $EF_{3\ DS}$ to indicate they were derived from modelling of the dataset. However, it is important to note that there were several gaps in the EF_3 dataset: these are indicated by the grey cells used in Table 13. We therefore were required to estimate values where gaps existed in the dataset. For dairy on lowland and beef cattle on low slopes, we assumed there was no significant difference in EF_3 between the two topographies for these two livestock classes (Kelliher et al. 2014a), therefore missing values were estimated using data from within the same season. For sheep and beef on medium and steep sloping hill country, there was no general pattern to the data. Therefore, in the absence of any other statistical approach, we estimated missing values by calculating the mean of available seasonal EF_3 values for a particular N source x livestock class x slope; these estimates therefore may not be representative of their associated season. There was no suitable alternative approach for estimating missing values.

Following estimation of seasonal EF_3 values via two approaches, we assessed how well the approaches compared. We restricted this comparison to dairy urine on lowland pastures, as this particular N source and topography class had the largest number of EF_3 values (323 replicate-level values). However, even for dairy urine on lowland pasture, only 17 of the values (or 5%) were generated in summer field trials. In contrast, there were 151 values (or 47%) generated from autumn trials while spring and winter had 76 and 79 values each. For this comparison, we used unadjusted $EF_{3\ SWC}$ values i.e. the average of the seasonal values were not adjusted by 3% to align with the annual EF_3 figures, in contrast to the inventory modelling (Table 13).

Our assessment suggests that for autumn, winter and spring, the modelled seasonal EF_3 values for dairy urine on lowlands are relatively similar to the measured means, providing a degree of confidence in the modelled results for this N source (Fig. 18). However, for summer, the modelled EF_3 value of 0.90% was significantly greater than the measured mean of 0.30% ($P < 0.05$). This suggests, for this particular N source, either an error in the modelled term based on the soil water balance and corrected for temperature (van der Weerden et al. 2014) and/or poor estimation of a summer EF_3 using the current dataset: each potential error is explored below.

The soil water balance (SWB) model used for estimating dairy urine EF_3 values had been validated against NIWA weather stations across New Zealand (van der Weerden et al. 2014). A relationship between soil water content and dairy urine EF_3, with an R^2 = 0.50, was used to estimate a monthly mean EF_3 value. The mean EF_3 value for the three summer months was 0.57% (derived from data in Table 7 of van der Weerden et al. 2014); this value was then adjusted upwards to 0.90% for the effect of temperature on biological processes, where it was assumed the rate would increase three-fold for every 10 ^oC temperature increase. Therefore, possible sources of error in $EF_{3\ SWC}$ include the soil water content – EF_3 relationship, considering soil water content explained only 50% of the variation in EF_3, and the temperature correction based on a Q_{10} of 3 may have been too large.

The modelled dairy urine EF_3 value of 0.30% was derived from the current dataset, which contains only two summer field studies, both conducted in Waikato. One study was conducted on a poorly drained soil, where the untransformed arithmetic mean EF_3 was 0.17%, while the other study was conducted using a freely drained soil, producing a raw mean EF_3 of 0.52%. These two studies are the only available data for estimating N_2O emissions from dairy urine deposited onto pastures in summer, therefore is unlikely to represent a national summer EF_3 value. The difference in modelled and measured summer values provides evidence for the need for further research to improve our estimation of summer N_2O emissions from this source.

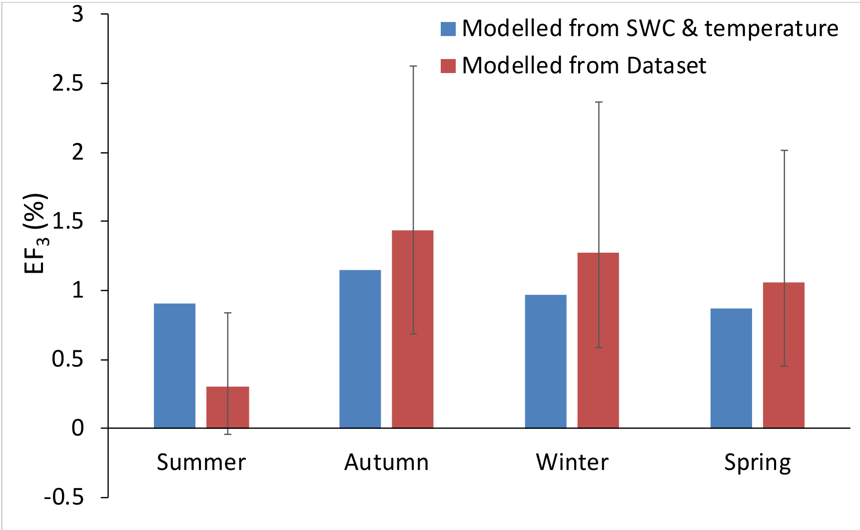

Fig. 18. Comparison of seasonal dairy urine EF_3 values for lowland grazed pastures based on (i) modelling of soil water content (SWC) and temperature (from van der Weerden et al. 2014), and (ii) modelling of current dataset limited to dairy urine on lowlands.

6.3 Scenarios

To assess the impact of employing monthly or seasonal emission factors on calculated N_2O emissions, we carried out the following scenarios. Scenario 1 represents a baseline estimation of the N_2O inventory using annual average EF_3 values, scenarios 2-5 represent a combination of baseline and monthly or seasonal EF_3 values, where monthly or seasonal EF_3 were modelled from soil water content and temperature ($EF_{3\ SWC}$) and scenario 7 used EF_3 values modelled from the current dataset ($EF_{3\ DS}$). For scenarios 1-6, annual dung EF_3 values were employed. For scenario 7, modelled seasonal dung EF_3 values ($EF_{3\ DS}$) were used.

1. Dairy, beef, deer and sheep annual urine EF_3 (baseline)

Annual dairy urine EF_3 of 1%, with annual beef, deer and sheep EF_3 values for different slope classes based on Saggar et al. (2015).

2. Dairy monthly urine $EF_{3\ SWC}$ (with annual urine EF_3 for beef, deer and sheep)

Monthly dairy urine $EF_{3\ SWC}$ based on modelled values from van der Weerden et al. (2014) with annual beef, deer and sheep EF_3 values for different slope classes based on Saggar et al. (2015).

3. Dairy seasonal urine $EF_{3\ SWC}$ (with annual urine EF_3 for beef, deer and sheep)

Seasonal dairy urine $EF_{3\ SWC}$ based on three-monthly averages of monthly values, from (2) above. Annual beef, deer and sheep EF_3 values for different slope classes based on Saggar et al. (2015).

4. Beef, deer and sheep monthly $EF_{3\ SWC}$ (with annual urine EF_3 for dairy)

Monthly beef, deer and sheep urine $EF_{3\ SWC}$ values for different slope classes based on Saggar et al. (2015) and disaggregated by month. Annual dairy urine EF_3 of 1% employed.

5. Beef, deer and sheep seasonal $EF_{3\ SWC}$ (with annual urine EF_3 for dairy)

Seasonal beef, deer and sheep urine $EF_{3\ SWC}$ values for different slope classes based on three-monthly averages of monthly values, from (4) above. Annual dairy urine EF_3 of 1% employed.

6. Combined effect of seasonal dairy, beef, deer and sheep urine $EF_{3\ SWC}$ (3) and (5).

Seasonal urine $EF_{3\ SWC}$ values employed for all livestock classes.

7. Seasonal dairy, beef, deer and sheep urine and dung $EF_{3\ DS}$ based on the current dataset.

Seasonal urine $EF_{3\ DS}$, derived from modelling of the current dataset, were employed for all livestock classes, where beef EF_3 values were used to represent deer N_2O emission factors.

6.4 Results and Discussion from scenario modelling

6.4.1 Dairy cattle

The monthly variation in calculated N_2O emissions was similar for all three dairy cattle EF_3 scenarios (i.e. using annual, monthly or seasonal values). This suggests that the temporal variation in emissions is largely driven by the variation in monthly N_{ex} activity data (Appendix A), rather than the EF_3 scenario (Fig. 19).

On an annual basis, employing monthly urine $EF_{3\ SWC}$ values reduced the calculated total direct N_2O emissions from dairy cattle by 1.5%, while seasonal EF_3 values resulted in a smaller reduction of 0.9% (Fig. 20).

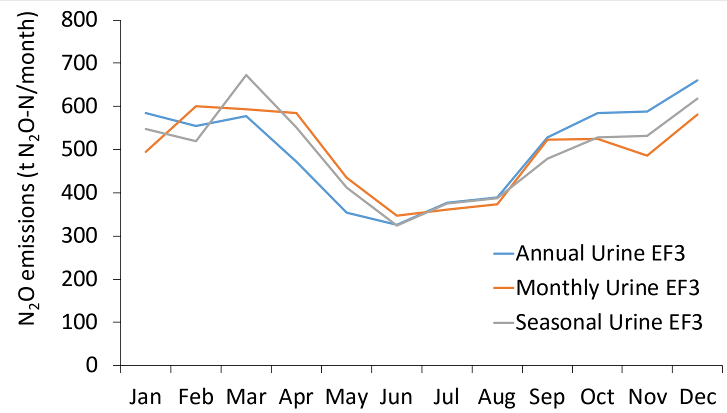

Fig. 19: National monthly variation in estimated N_2O emissions from dairy cattle when employing annual (scenario 1), monthly (scenario 2) or seasonal (scenario 3) urine EF_3 values.

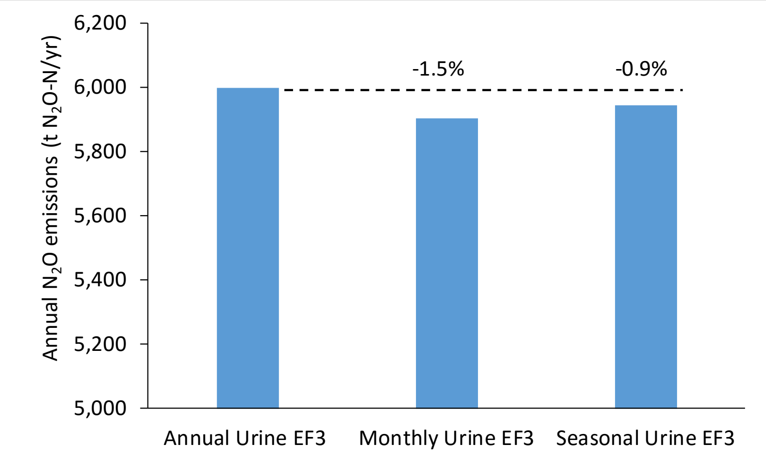

Fig. 20: Change in annual N_2O emissions from dairy cattle when employing monthly (scenario 2) or seasonal (scenario 3) urine $EF_{3\ SWC}$ values. Note Y-axis scale.

6.4.2 Beef, sheep and deer

Beef showed greater temporal variation when monthly or seasonal urine $EF_{3\ SWC}$ values were employed compared to an annual EF_3, with the increase in calculated emissions in autumn being greater than the reduction in emissions in spring and summer (Fig. 21). This led to an overall increase in calculated annual direct N_2O emissions of 1.8-1.9% from beef excreta when either monthly or seasonal urine $EF_{3\ SWC}$ values were used (Fig. 22).

In contrast, for sheep and deer, the degree of temporal variation appears similar for the three $EF_{3\ SWC}$ options (Fig. 23 and 24), although the annual N_2O emission was calculated to be 1.1-1.6% lower compared to adoption of annual urine EF_3 values (Fig. 25 and 26).

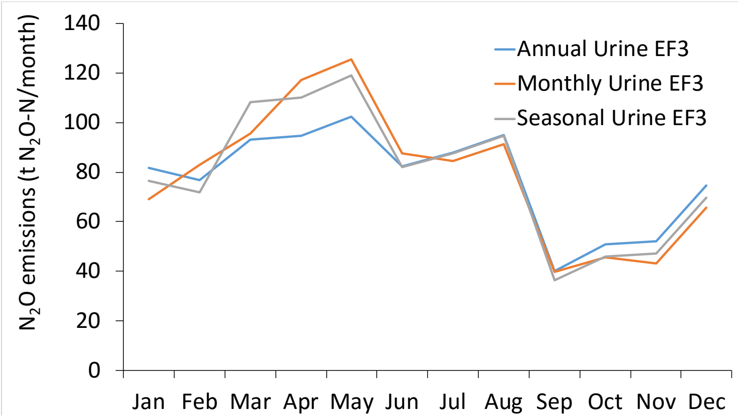

Fig. 21: National monthly variation in estimated N_2O emissions from beef cattle when employing annual (scenario 1), monthly (scenario 4) or seasonal (scenario 5) urine $EF_{3\ SWC}$ values.

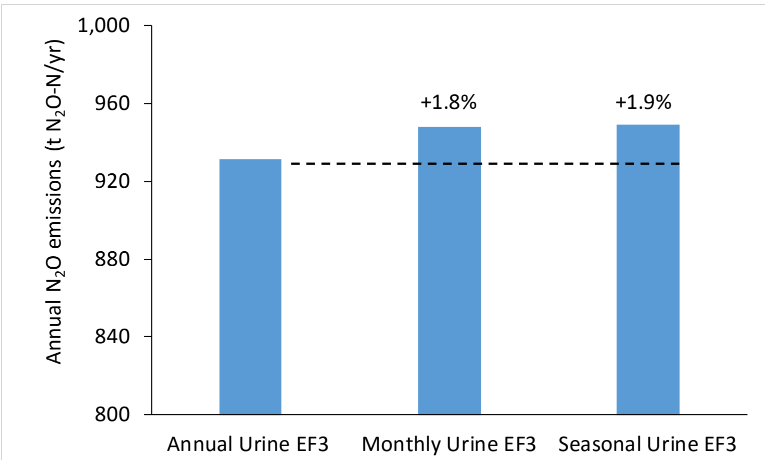

Fig. 22: Change in annual N_2O emissions from beef cattle when employing monthly (scenario 4) or seasonal (scenario 5) urine $EF_{3\ SWC}$ values. Note Y-axis scale.

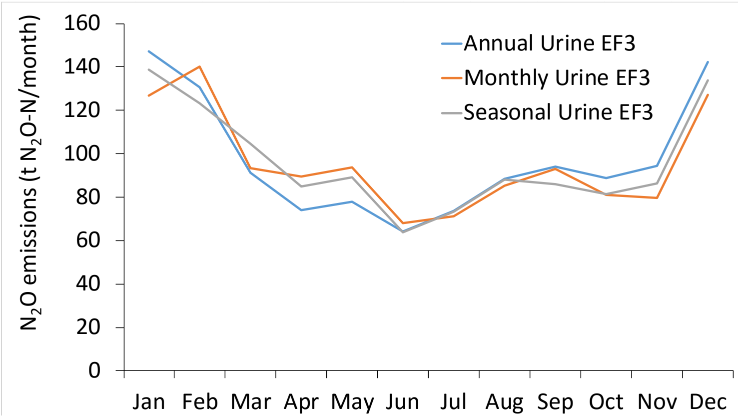

Fig. 23: National monthly variation in estimated N_2O emissions from sheep when employing annual (scenario 1), monthly (scenario 4) or seasonal (scenario 5) urine $EF_{3\ SWC}$ values.

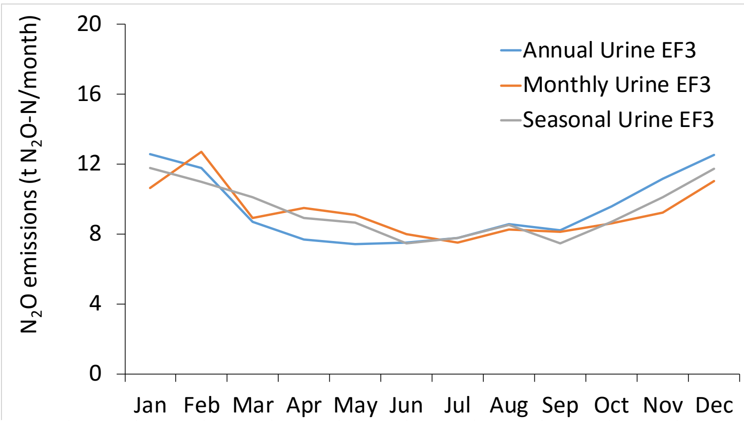

Fig. 24: National monthly variation in estimated N_2O emissions from deer when employing annual (scenario 1), monthly (scenario 4) or seasonal (scenario 5) urine $EF_{3\ SWC}$ values.

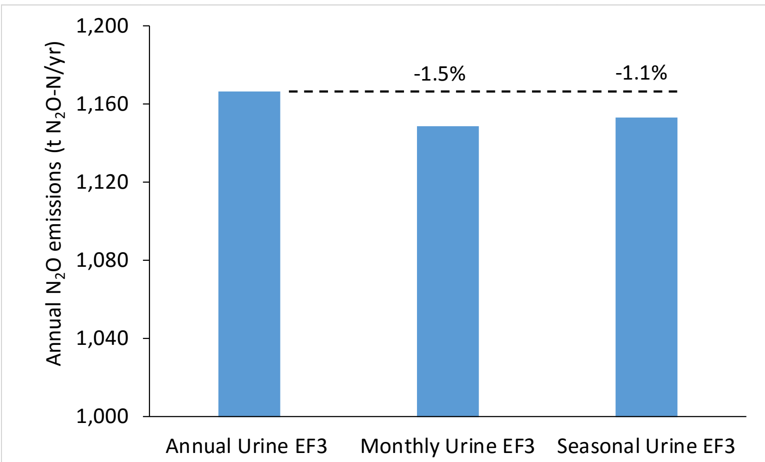

Fig. 25: Change in annual N_2O emissions from sheep when employing monthly (scenario 4) or seasonal (scenario 5) urine $EF_{3\ SWC}$ values. Note Y-axis scale.

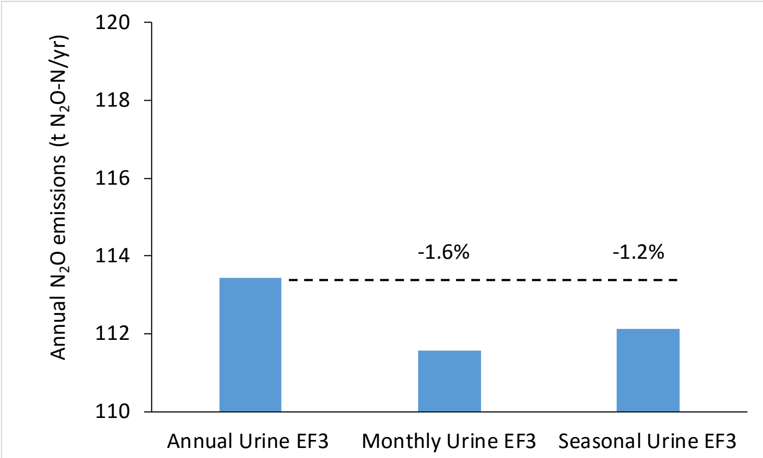

Fig. 26: Change in annual N_2O emissions from deer when employing monthly (scenario 4) or seasonal (scenario 5) beef urine $EF_{3\ SWC}$ values. Note Y-axis scale.

6.4.3 All grazing livestock classes

When seasonal urine EF_3 values based on soil water content and temperature ($EF_{3\ SWC}$) were employed for all livestock classes, we observed a 0.6% reduction in the calculated total N_2O emissions from livestock grazing (Fig. 27). The percentage change is less than those calculated for the individual livestock classes due to the decrease in emissions for dairy, deer and sheep being partially offset by the increase in calculated emissions from beef excreta. However, it is challenging to determine how well these estimated EF_3 values reflect actual EF_3 values. The earlier comparison of seasonal dairy urine EF_3 values restricted to lowland pastures (Fig. 18) would suggest that, for three seasons, the methods are comparable. But the large difference in summer EF_3 values based on modelling of soil water content and temperature vs. modelled from the current dataset would suggest more research is required to improve our knowledge of summer N_2O emissions.

When modelled seasonal urine and dung EF_3 values based on the current dataset were used, the estimate of the national N_2O inventory declined by 8.6% (Fig. 27). The reasons for the difference in the estimated annual N_2O inventory based on seasonal $EF_{3\ SWC}$ and $EF_{3\ DS}$ values were two-fold. Firstly, the $EF_{3\ SWC}$ approach was applied to urine only, as there are no modelled monthly or seasonal EF_3 values for dung. However, the impact of not including dung can be considered as minor, as dung represents approximately 8% of N_2O emissions from excreta, when considering dung represents 27-34% of total excreta (Ministry for the Environment, 2014) and the EF_3 value for dung is 25% of that for urine (Table 13). Secondly, and more importantly, the seasonal $EF_{3\ SWC}$ values were based on monthly values which had been adjusted (increased by 3%) to ensure the average of the monthly values was equivalent to the annual EF_3 (Table 13). This was done to provide an assessment of the effect of a monthly or seasonal disaggregation of the current annual urine EF_3 value of 1%. In contrast, the $EF_{3\ DS}$ approach used the modelled output from the statistical analysis of the dataset without any adjustment to the annual average values. However, when correcting the difference in the annual N_2O inventory emissions for the 3% adjustment to the urine EF_3 values, there is still a 5% difference in the emissions between the two seasonal approaches (8.6% – (3.0% + 0.6%) = 5%). It could be argued that seasonal EF_3 values based on the current dataset provide a more accurate estimation of the inventory, given both N_{ex} and EF_3 values are disaggregated by livestock class, slope class (where differences have been observed), season, as well as excreta type; the latter being already adopted as a Tier 2 approach within the New Zealand agricultural greenhouse gas inventory. As noted earlier, there are gaps in the dataset, which were estimated for this modelling exercise, and that some significant sources (such as dairy urine in summer) have very few measured values.

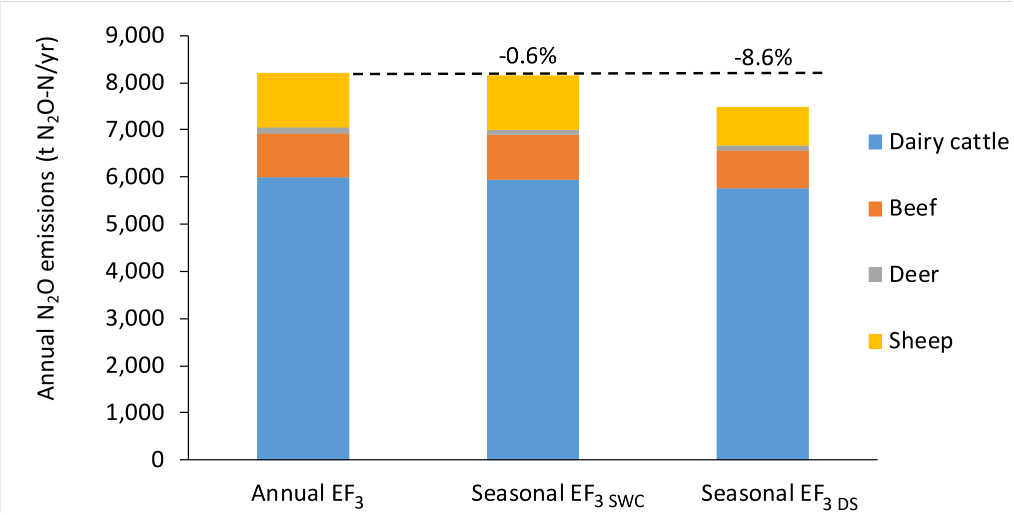

Fig. 27: Change in annual N_2O emissions from livestock when employing seasonal $EF_{3\ SWC}$ values (urine only) or seasonal $EF_{3\ DS}$ values (urine and dung) for all 4 grazing livestock classes (scenario 1 vs. scenario 6 vs. scenario 7).

In conclusion, based on the available data, it is challenging to determine appropriate values for summer EF_3. The earlier comparison of seasonal dairy urine EF_3 values restricted to lowland pastures (Fig. 18) would suggest that, for three seasons, the two methods employed for estimating seasonal EF values are comparable (at least for this N source and topography). However, the large difference in summer EF_3 values, based on (i) modelling of soil water content and temperature and (ii) modelling of the current dataset, would suggest more research is required to improve our knowledge of summer N_2O emissions. Summer is also the season when the greatest change in soil water content can occur, due to the large water use by plants relative to rainfall: large changes in soil water content will have a direct impact on N_2O emissions. Generating more robust estimates of summer EF_3 values will ensure estimates are less likely to be influenced by any one study. By expanding the summer EF_3 dataset, it will be possible to calculate either an improved estimate for annual EF_3 values or generate more robust seasonal EF_3 values, leading to improved accuracy of the inventory.

6.5 Summary of Key Points

From the inventory scenario modelling, the following key points were made.

- To assess the impact of adopting seasonal EF_3 values on the national N_2O inventory for livestock grazing, seasonal EF_3 values were estimated using two approaches: the first based on modelling of soil water content and corrected for temperature effects ($EF_{3\ SWC}$) and the second based on the current dataset ($EF_{3\ DS}$).
- A direct comparison of the two approaches, using dairy urine on lowland as the N source, showed comparable EF_3 values for autumn, winter and spring. However, there was a significant difference in the values for summer, suggesting further research is required to improve the estimation of summer EF_3.
- When seasonal $EF_{3\ SWC}$ values were employed, estimation of annual livestock N_2O emissions declined by 0.6% compared to losses based on annual EF_3 values.
- When seasonal $EF_{3\ DS}$ values were, i.e. EF_3 values based on the analysis of the current dataset, estimation of annual livestock N_2O emissions declined by 8.6% compared to estimated losses using annual EF_3 values. Using the current dataset to estimate EF_3 provides a more accurate estimation of the inventory, given both N_{ex} and EF_3 values are disaggregated by livestock class, slope class, season, as well as excreta type.
- However, the current dataset has a limited amount of summer EF_3 data (such as dairy urine).
- Better estimates of summer EF values would allow an improved estimate for annual EF values.
- Generating more robust summer EF values would also allow better estimation of seasonal EF_3 values, which could be employed within the national inventory methodology, leading to improved accuracy of the inventory.

7. Conclusions

Following an update of the existing EF_3 and EF_1 dataset, the number of summer EF_3 values represented only 13% of the total EF_3 dataset while summer EF_1 values were only 9% of the total EF_1 dataset. Seasonality had a significant effect on EF_3, with winter producing the highest EF_3 values, and summer producing the second highest EF_3 values. For urine, the overall mean summer EF_3 value was 1.00%, which was between the values for winter (1.10%) and autumn (0.87%).The spring value was lowest, at 0.40%. For dung, summer and winter had the highest mean EF_3 value (0.23 and 0.26%, respectively), while the autumn was 0.10% and spring was lowest, at -0.18%. Soil drainage class, topography, region and relative rainfall all showed a significant effect on seasonal EF_3. However, due to the unbalanced nature of the dataset, interpretation of the some of the effects was challenging. A recent study on irrigation and N_2O emissions concluded there is evidence that irrigated soils emits more N_2O, however the magnitude of its effect is variable. Limited or no data made it difficult to provide 'irrigation' EF values for urine, dung and urea fertiliser.

Urea fertiliser EF_1 showed a non-significant seasonal effect, although summer produced the lowest seasonal mean of 0.07%, which was 18 times lower than the winter value of 1.27%. Region has a significant effect on seasonal EF_1 values, whereas drainage class, topography and relative rainfall did not influence seasonal urea EF_1 values.

Results from an uncertainty analysis showed that when a single annual EF_3 value was used, the estimated 95% confidence interval (CI) of the N_2O inventory was ± 89%. However, when seasonal EF_3 values were used, the 95% CI increased by nearly a factor of two to ± 158%. As expected, using seasonal EF_3 values increases the uncertainty, however the accuracy of the national inventory will be improved.

When national N_2O emissions were modelled using seasonal EF_3 values based on the analysis of the current dataset, estimation of annual livestock N_2O emissions declined by 8.6% compared to losses based on annual EF_3 values. When seasonal urine EF_3 values based on soil water content and corrected for temperature effects were used, estimation of annual livestock N_2O emissions declined by 0.6% compared to estimated losses using annual EF_3 values. We suggest that using the current dataset to estimate EF_3 provides a more accurate estimation of the inventory, given both N_{ex} and EF_3 values are disaggregated by livestock class, slope class, season, as well as excreta type. A disaggregated EF_3 approach allows the inventory to respond to changes in animal distributions by landscape and season. However, the current dataset has a limited amount of summer EF_3 data (such as dairy urine). Better estimates of seasonal EF's would improve the accuracy of the inventory.

8. Recommendations

Based on our review, there is currently insufficient data to justify the adoption of seasonal EF_3 values for estimating emissions within the national inventory, primarily due to a limited amount of summer EF_3 data. We have summarized key knowledge gaps and prioritized future work to address these gaps.

1. Dairy excreta currently represent close to 50% of N_2O emissions from livestock excreta. With the proposed changes to the inventory methodology for sheep, beef and deer, the contribution of dairy cattle to total N_2O emissions will increase markedly. Given that the majority of dairy cattle graze lowland pastures and the limited summer EF_3 data for this N source (2 field studies providing 17 replicate-level values), we recommend summer field trials are conducted across representative regions to improve our estimation of dairy cattle urine and dung EF_3.
2. There is a need to improve our knowledge on the influence of irrigation on summer N_2O EF_3 and EF_1. We recommend summer field trials in regions where irrigation represents a significant proportion of pastoral land. N sources should focus on dairy excreta and urea fertiliser. In addition, non-irrigated treatments should be included to improve our understanding of the impact of irrigation on N_2O emissions.
3. We have identified summer sheep EF_3 data as a knowledge gap. We recommend field trials are conducted in summer across key regions to quantify N_2O EF_3 for this N source on all three slope classes.
4. Field trials under controlled conditions (e.g. controlled 'rainfall') will assist in understanding the drivers of variability between soils (e.g. contrasting drainage classes) and N sources for different seasons.

While not specifically related to summer EF knowledge gaps, our analysis showed large regional variation in EF_3 values. Therefore, we suggest future research projects carefully consider selecting appropriate regions that are representative of livestock numbers and are additional to those currently used. An example of a field experiment adopting this approach is the recently initiated dairy and beef hill country experiment, where field trials are under way in Northland, and trials next year are planned for Bay of Plenty.

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11. Appendices

Table A1: Monthly nitrogen excretion rates (N_{ex}, t N/month) for different animal type and slope classes. Based on the 2012 National GHG inventory (MPI, 2014).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dairy	73378	69598	72441	59257	44388	40862	47180	48830	66294	73254	73719	82792
Beef – low slope	4815	4526	5489	5585	6028	4853	5181	5605	2369	3005	3082	4391
Beef – medium & steep slope	20185	18974	23011	23415	25272	20347	21719	23495	9931	12595	12918	18409
Sheep – low slope	17555	15585	10882	8814	9282	7657	8790	10562	11202	10612	11252	16964
Sheep – medium & steep slope	53745	47715	33318	26986	28418	23443	26910	32338	34298	32488	34448	51936
Deer – low slope	912	852	630	557	538	544	565	622	596	695	808	907
Deer – medium & steep slope	2578	2408	1780	1573	1522	1536	1595	1758	1684	1965	2282	2563
Total	173168	159658	147551	126187	115448	99242	111940	123210	126374	134614	138509	177962