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Analysis of N_2O emission factor data from field trials and N_2O emissions inventory uncertainty assessment

- Final report

MAF POL 12206 (IR-A1and IR-B2: N_2O field trials and update of uncertainty analysis)

16 December 2011

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Francis Kelliher, Neil Cox, Harold Henderson, Tony van der Weerden, Catie Gongol, Jiafa Luo, Mike Rollo, Cecile de Klein, Keith Cameron and Donna Giltrap

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1. Executive Summary

The aims of this project were:

1. To conduct a meta-analysis of field trial data to assess the effects of a range of concurrently, measured variables on EF3 and EF1 values,
2. To recommend the most appropriate disaggregation level for country-specific EF3 and EF1 values and provide updated values, and
3. To assess the effect of these updated values on the uncertainty of NZ's inventory of agricultural soil N_2O emissions.

Anticipating the variability of EF3 would mostly determine the uncertainty of NZ's inventory of agricultural soil N_2O emissions, a secondary aim was to explore the effects of rainfall and soil fertility on EF3.

We compiled NZ's available data of the direct nitrous oxide (N_2O) emission factor called EF3 for grazing ruminant urine and dung excreta and EF1 for nitrogen (N) fertiliser. These data came from field trials where direct N_2O emissions were measured after a known quantity of N was applied to soils. Thus, these trials have not included other effects of grazing animals such as compaction of soils. The EF1 and EF3 data have been subjected to a meta-analysis. Rainfall determines soil wetness that can affect EF3 and EF1. After N application to soils, most of the total N_2O emissions for a field trial occur within one month. On this basis, we argued that rainfall during the first month after N application to soils should be indicative. Consequently, for each field trial, measured rainfall was summed for the first 30 days. These rainfall values were then deemed typical or atypical by comparison to long-term monthly rainfall statistics based on data from the closest weather station. After completing the EF3 and EF1 meta-analysis, we used the results to assess the uncertainty of NZ's inventory of agricultural soil N_2O emissions by analytical and Monte Caro numerical simulation methods.

Prior to the meta-analysis, we postulated that soil fertility could affect EF3. For a subset of EF3 replicate-level data for dairy cattle and sheep urine applied to lower slope positions at 4 hill country sites in 3 regions, topsoil fertility data as expressed by the phosphate level (Olsen P) were available for analysis. A curvilinear relation, accounting for 67% of the variability in dairy cattle and sheep urine EF3 (n = 38), and suggested that EF3 and the Olsen P level increased together. This relationship looks promising and warrants further research. Unfortunately, the Olsen P level in soils has not been measured in other field trials, so further data analyses were not possible. Further research is also warranted to examine the effects of other indicators of soil fertility (e.g. available N) on EF3 and EF1.

For dairy cattle and sheep urine, dairy cattle and sheep dung and urea fertiliser, there have been 128 EF3 and EF1 field measurement trials including 25, 40, 60 and 3 which began in autumn, winter, spring and summer, respectively. For meta-analysis, the paucity of data for summer made it difficult to determine if there had been a seasonal effect. Moreover, there have been no EF3 field measurement trials during summer on seasonally-irrigated soils. On the basis of meta-analysis, mean values of EF1 and separate EF3 means for urine and dung should be used in NZ's inventory because EF3 and EF1 were significantly affected by the form of nitrogen applied to soils (urea fertiliser, urine and dung). Further disaggregation of EF3 and EF1 based on topographic type (lowland versus hill country), soil drainage class (freely versus poorly drained), rainfall and season was not warranted. This means knowledge of these factors did not significantly affect description of the EF3 and EF1 data by the meta-analysis.

A value of 1% should be used in NZ's inventory for the EF3 of dairy cattle, beef cattle and sheep urine on the basis of meta-analysis of data from 75 field measurement trials which yielded mean values of EF3 for dairy cattle and sheep urine which were not significantly different from each other or from 1%. A value of 0.25% should be used for the EF3 of dairy cattle, beef cattle and sheep dung on the basis of the earlier recommendation for this value and support from the meta-analysis. The meta-analysis of data from 36 field measurement trials yielded a mean EF3 of 0.3% for the dung of dairy cattle, beef cattle and sheep and no significant differences amongst animal types. This mean EF of 0.3% was not significantly different to the earlier recommended value of 0.25%. However, the mean EF of 0.3% was significantly less than the mean EF3 for dairy cattle and sheep urine from the meta-analysis.

A value of 0.7% could be used for EF1 on the basis of meta-analysis of data from 19 field measurement trials. This mean was significantly less than those of EF3 for dairy cattle and sheep urine. Calculations using activity data for the year 2009 indicated reducing EF1 from the current value of 1% to 0.7%, and no other changes, would reduce NZ's inventory of agricultural soil N_2O emissions from 9,918 Gg CO_2-eq to 9,427 Gg CO_2-eq, a reduction of 427 Gg CO_2-eq which has an annual monetary value of NZ$12.3 M if one tonne of CO_2-eq is worth NZ$25. However, we think further EF1 measurement trials are needed to support acceptance of reducing EF1 from 1 to 0.7% by the international community. Such trials should include more soils and sites, including hill country, and for completeness, urea and compound fertilisers such as DAP as well as mitigation products. Statistical analyses have shown the subset of EF1 data analysed here is variable with a mean of 0.7 ± 0.4% for 95% confidence. Future trials should also provide a better balance between regions as 13 of the current 19 trials where located at Ruakura, 10 trials on a poorly-drained soil, Te Kowhai silt loam, and 3 trials on a freely-drained soil, Horotiu silt loam. For 16 of 19 trials, the urea fertiliser application rate was 50 kg N/ha. In future, it could also be useful to include more than one fertiliser application rate in field trials.

According to analytical and Monte Carlo numerical simulation methods, assuming independence of the variables, NZ's inventory of agricultural soil N_2O emissions for the year 2009 should be reported as 32.0 ± 21.0 Gg for 95% confidence. A consistency of results from different methods gave us confidence in our assessment of the inventory's uncertainty. To our knowledge, the uncertainty of a national inventory of agricultural soil N_2O emissions has not previously been assessed by an analytical method. This required us to develop a different way of expressing the inventory and adopting and developing a seminal analysis for the variance of a product published by Goodman in 1960. The 95% confidence limit should be considered a lower limit because the inventory's uncertainty level could be up to 15% larger if the variables had been positively and perfectly correlated (correlation coefficient = +1). For the N_2O emissions from agricultural soils, quantifying this correlation will be difficult and the available experimental data were considered equivocal. The NZ inventory's uncertainty and dependence on variable correlation is largely determined by the emission factor standard error, estimated by meta-analysis of the field trial data to be 32% of the mean. Activity data determine the corresponding nitrogen application rate onto agricultural soils and the estimated standard error for this component of NZ's inventory was 6% of the mean.

2. Introduction

This project will make 2 significant contributions to NZ's agricultural soils nitrous oxide (N_2O) emissions inventory (hereafter, inventory). Firstly, we will compile and analyse the available direct emission factor data (EF3 for grazing ruminant urine and dung excreta and EF1 for nitrogen (N) fertiliser). This will either confirm the values of EF3 and EF1 used in the inventory or generate new values based on a compilation that will be as complete and up-to-date as possible. Second, we will assess the inventory's uncertainty using the analysed data.

NZ's inventory is strongly influenced by EF3 and EF1, so their determination is important. While some field measurement trials were conducted prior to the inception of NzOnet, the New Zealand nitrous oxide expert group, the vast majority of trials have taken place since the year 2000. Moreover, most trials have been conducted during the past three years including, for the first time, soils located in hill country that comprises about half the national area of grazed pasture. Another recent focus of measurements has been the determination of EF3 for dung. There have also been a number of EF1 field trials with urea N fertiliser. It is thus timely to comprehensively compile and analyse the available EF3 and EF1 data, seeking to improve the inventory.

We have compiled replicate-level, EF3 data for sheep and cattle excreta applied to soils and EF1 data from field trials that have been conducted in New Zealand including those with nitrification inhibitors (DCD). This has created a unique, comprehensive data set for analyses and builds upon the existing N_2O emission factor database.

Anticipating the variability of EF3 would mostly determine the uncertainty of NZ's inventory of agricultural soil N_2O emissions, a secondary aim was to explore the effects of rainfall and soil fertility on EF3. Rainfall has been reported by many studies to be a key driver of N_2O emissions. Thus, EF3 and EF1 values from trials may be influenced by the rainfall. On this basis, atypical rainfall during a trial may indicate atypical values of EF3 and EF1. We will compare rainfall measured during trials and long-term rainfall statistics from the closest weather station in order to assess representativeness of the EF3 and EF1 measurements. Earlier work suggested that EF3 was positively related to the topsoil Olsen P level (de Klein et al. 2010). We will explore this relationship further.

3. Project objectives

- To compile EF3 and EF1 data available from field trials
- To compile rainfall data for each field trial as well as long-term rainfall and evaporation data
- To analyse the compiled rainfall and EF3, EF1 data
- To determine if EF3 is related to a soil fertility measurement
- Based on the data analyses, assess uncertainty of the agricultural soils N_2O emissions inventory using Monte Carlo and analytical methods

4. Approach

4.1 Compilation of N_2O emission factor (EF3 and EF1) data

Available field trial data were compiled at the replicate level for dairy cattle and sheep urine and dung excreta and N fertiliser. These data included N application rates and cumulative nitrous oxide (N_2O) emissions rate (period when the mean of the treated replicates had N_2O emissions significantly greater than the mean of the controls). For each trial, rainfall for 30 days after treatment application was also compiled. The inventory uses net values of EF3 and EF1 (i.e. values calculated after subtracting background N_2O emissions from the control plots from the N-amended plot's N_2O emissions), but the compiled data allowed analyses to proceed on the bases of net and gross (i.e. do not subtract the background emissions) values. The EF3 and EF1 data compiled will include trials with nitrification inhibitors. Permission was sought from the NOMR (nitrous oxide mitigation research jointly funded by MAF, Dairy NZ, Fonterra, PGGRC, and the fertiliser industry) and P21 (pasture 21 research programme jointly funded by Dairy NZ, Fonterra, Beef + Lamb NZ and Ministry of Science and Innovation) investors for inclusion of these data.

The N_2O emission factor database includes replicate and higher levels of aggregation such as a treatment mean. For this project, replicate–level data was required for analyses including the probability distribution of EF3 and EF1 for inventory uncertainty assessment. Thus, this project has developed the database. Data compilation was done by the researchers who conducted the relevant field trials and this report's authors include the principal research providers.

4.2 Does soil fertility affect EF3?

To set the scene for meta-analyses in response to the posed question, we briefly summarise preliminary results from an earlier hill country study reported by de Klein et al. (2010). This hill country field trial included 4 soils in 3 regions. The soils were a freely-draining Dunmore silt loam soil located at Whatawhata in the Waikato region, a freely-draining Makotuku fine sandy loam soil at Westview Farm near Awahou, Pohangina Valley, in the Manawatu region, a poorly-draining Wainui silt loam soil at Ballantrae in the Southern Hawke's Bay region but located close to the Westview Farm site, and a freely-draining Kiteroa brown soil at Hindon in the Otago region. At all of these field trial sites, sheep had grazed and the Olsen P level was measured in soil samples (depth of 0 – 7.5 cm) taken across potential plots to identify, and avoid, camp sites. For the trials, sheep and dairy cattle urine were applied to randomly-selected subplots at two slope positions (low, < 12°, and medium, 12 – 25°) at rates up to 464 and 564 kg N/ha, respectively, and N_2O emissions measured afterwards. Where sheep urine had been applied to subplots, linear regression of soil Olsen P and EF3 accounted for 56% of the variability in the plot level data (4 soils and 2 slope positions, so n = 8, de Klein et al. 2010). Soil phosphorus (P) should not affect N_2O emissions directly, but in soils of sheep-grazed campsites, the N and P cycles should be closely linked through the relatively high returns of excreta. On the basis of connected P and N cycles, and predicated on sufficient soil wetness, it has been postulated that a positive correlation between Olsen P and EF3 could be attributed to the de-nitrification rate increasing with increasing soil fertility as indicated by the Olsen P level. As implied, keeping in mind that sheep and dairy cattle urine had been applied to subplots, N-substrate supply rate from the organic matter may be a determinant of the N_2O emission rate from urine-treated soils, so EF3 would also be affected. Further investigation of the relationship between soil fertility status/Olsen P level and EF3 seemed warranted. To proceed, EF3 of each subplot or replicate of the hill country trial was re-calculated using log transformation with a constant added before taking logs to ensure that the analysis assumptions of constant variance and approximate normality (of the residuals) were met. Based on inspection of these data and residuals, a constant of 1 was appropriate, so this was used.

4.3 Was rainfall during the first month of field trials typical?

Rainfall determines soil wetness that can affect EF3 and EF1. After N application to soils, most of the total N_2O emissions occur within one month. On this basis, we argued that rainfall during the first month after N application to soils should be indicative. Consequently, for each field trial, the measured rainfall was summed for the first 30 days after N application to soils. These rainfall values were then deemed typical or atypical by comparison to long-term monthly rainfall statistics based on data from the closest weather station. When a trial began in the first half of a month, the comparison used rainfall statistics for that month. Alternatively, when a trial began in the second half of a month, the comparison used rainfall statistics for the following month. These statistics, including mean, maximum, minimum, 10 percentile and 90 percentile values, came from New Zealand Meteorological Service (1983). The validity of historical, long-term rainfall statistics for contemporary application was checked by analysis of 60 years of monthly rainfall data (1950 – 2009) from a weather station located near Ashburton, and there were no statistically significant time trends (Kelliher et al. 2011). For this study, there were 11 weather stations including Ballantrae 1 Woodville (in NZ Met. Serv. (1983), this station's index number was D05383), Finegard, Balclutha (I69273), Hamilton airport (C75832), Hindon Farm (I50721), Invercargill airport (I68433), Invermay, Taieri (I50831), Lincoln (H32641), Massey University (E05365), Milton (I69191), Ruakura, Hamilton (C75731) and Whatawhata (C75801).

Analyses of monthly rainfall data have shown the probability distribution is not a symmetrical, bell-shaped curve (that is, it is not normal). Consequently, assuming a normal probability distribution for monthly rainfall and generating a (single) standard deviation as the variability statistic would not be appropriate. Thus, we did not assume symmetry of the probability distribution for monthly rainfall values less than the mean versus greater than the mean. Instead, two values of the standard deviation were estimated, one for the portion of the distribution less than the mean (hereafter, the lower value) and the other for the portion of the distribution greater than the mean (upper value). When a trial's 30-day rainfall was less than the long-term mean, a first estimate of the lower standard deviation was the difference between long-term values of the mean and minimum divided by 3 ([mean – minimum]/3). The basis for this first lower value estimate was actually a normal distribution where the difference between the maximum and minimum will be equal to the six standard deviations, so the difference between the mean and minimum will be equal to three standard deviations. For monthly rainfall, the minimum value cannot be less than zero and minimum values from long-term records are generally close to zero, so efficient estimates. Likewise, estimating mean monthly rainfall values from long-term records should be efficient. Nevertheless, our first estimate of the lower standard deviation was checked by another estimate based on the difference between long-term values of the mean and 10 percentile divided by the absolute value of the Z statistic (for a normal distribution, there will be 1.282 standard deviations between 10 percentile and mean values; thus, [mean – 10 percentile]/1.282). Anticipating the results, little difference between two estimates of the lower standard deviation supported our argument that the minimum is an efficient estimate of the lower limit of monthly rainfall (namely, zero).

There should be no upper limit of monthly rainfall. This means an upper standard deviation (for the portion of the monthly rainfall distribution greater than the mean) should be greater than a lower standard deviation because the latter should be constrained by a lower limit of monthly rainfall equal to zero. A lack of upper limit for monthly rainfall also means a maximum value from a long-term record may not be an efficient estimate because it depends on a single value from the record. This may affect an upper standard deviation calculated according to ([maximum - mean]/3). Consequently, a second estimate of upper standard deviation was calculated according to ([90th percentile - mean]/1.282), utilising 90% of the record to determine the 90th percentile value. While the latter estimate was more likely to be the most appropriate, an upper standard deviation was the lesser of the two estimates.

4.4 Statistical meta-analyses of the compiled EF1 and EF3 data

Meta-analysis is a quantitative synthesis of results across multiple studies. This has the potential to overcome some of the limitations of low statistical power for individual studies and test whether the results have been general (Hungate et al. 2009, van Groningen et al. 2011). A meta-analysis will be conducted of the EF1 and EF3 data from 164 field trials, some conducted at multiple sites, and with multiple N sources (type of N applied to the soil). The trials varied in design and number of replicates. In all cases we have calculated a single value for EF1 or EF3 as (mean of treated reps – mean of control reps)/N applied; a second analysis was done on EF1 and EF3 calculated using the median of the reps rather than means. The field trials and sites were classified according to 2 drainage classes (free versus poor) and 2 topographic types (lowland versus hill country). For nearly all trials, rainfall measurements were provided by researchers, while soil water content measurements were provided for only 60% of the trials. Consequently, meta-analysis proceeded with the rainfall data. For the meta-analysis, a rainfall variable for each trial was created by first taking a ratio of the measured rainfall during the first 30 days relative to the typical monthly rainfall (see previous section). In order not to pre-suppose a relation between the rainfall ratio and EF3 and EF1, the rainfall ratio was grouped into 4 levels for the meta-analysis; namely, < 0.5, $0.5 <$ ratio ≤ 1.0, $1.0 <$ ratio ≤ 2.0 and > 2.0. Season for each trial was defined by determining which month the trial's 15^{th} 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.

Separating the effects of these factors from results of these field trials has been challenging due to confounding effects. For instance, many N sources are represented by only 2 or 3 trials and data for some N source was only available for lowland sites and others only on hill country sites. For example, all 18 trials that measured EF3 of dairy cattle dung were conducted at lowland sites, and trials at hill country sites have included only 5 of the N sources. To deal with these issues, data were analysed using a restricted maximum likelihood (REML) method. This is considered the most appropriate method to combine information across multiple trials. For REML, the fixed effects were N source, drainage class, topographic unit, rain ratio and season. The random effects were trial and site, recognising a number of trials had been conducted at multiple sites,

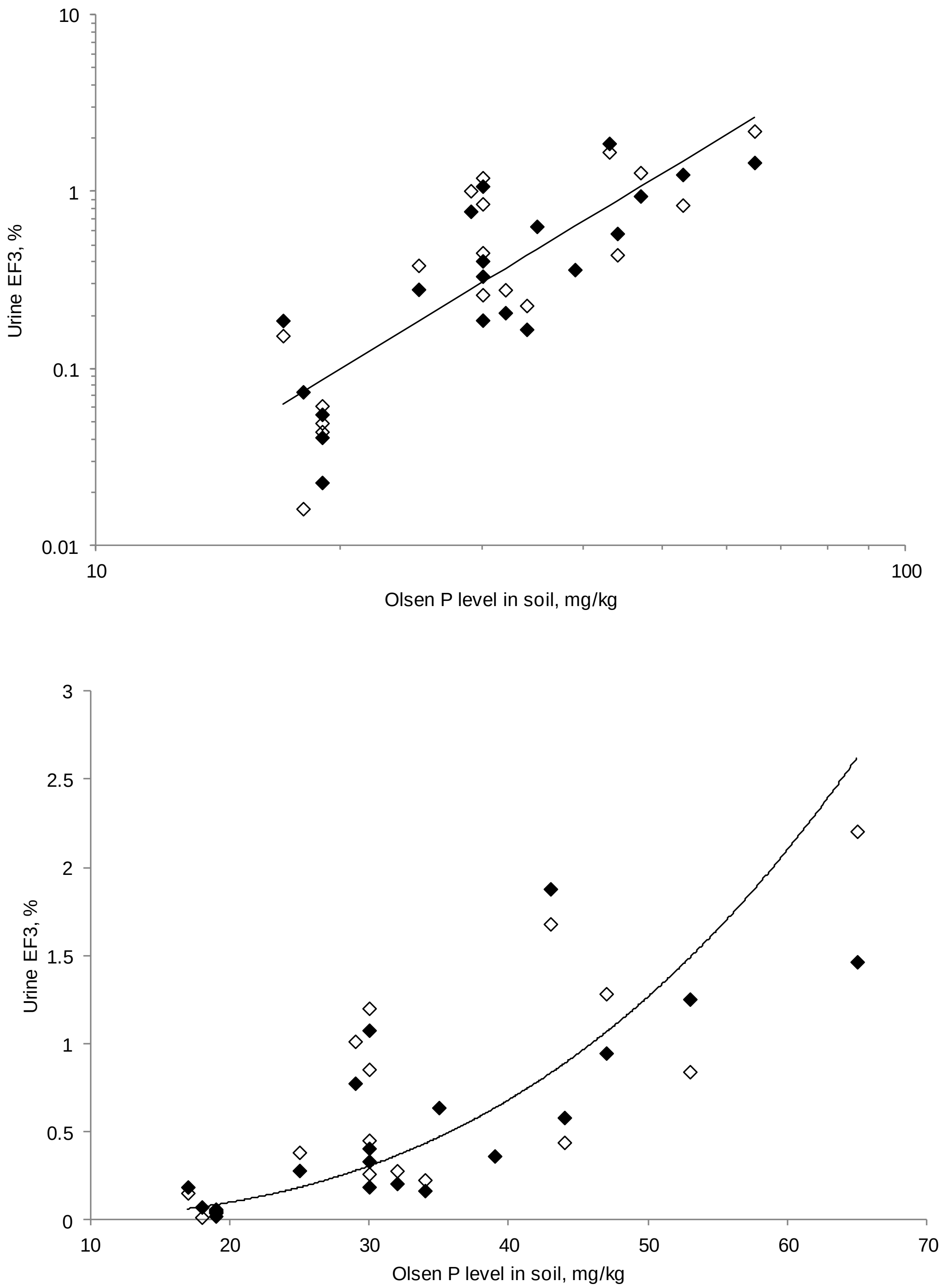
While 20 N sources had been specified by researchers, these were aggregated into 13 categories for analysis. These included dairy cattle urine, synthetic dairy cattle urine, dairy cattle urine + DCD, dairy cattle urine + urea fertiliser, dairy cattle dung, dairy cattle dung + DCD, beef cattle dung, sheep urine, synthetic sheep urine, sheep urine + DCD, sheep dung, urea fertiliser and urea fertiliser + DCD. Recently, all available data have been were synthesised to quantify the effect of DCD on dairy cattle urine EF3 (de Klein et al. 2011). This analysis did not account for the effect of soil temperature on DCD longevity in soils which can affect the performance of DCD in reducing EF3 and EF1 (Kelliher et al. 2008). While the meta-analysis of Kelliher et al. (2008) reported a functional relation between DCD half-life and soil temperature, they had analysed data from soil sample incubations where the temperature had been held constant. The relation may not apply exactly under field conditions where the soil is occupied by living pasture plants and appropriately integrating soil temperature measurements over time in conjunction with a EF3 field measurement trial would be challenging (for example, at what depth(s) should temperature sensors be located? How should one vertically integrate temperature measurements at different depths?). For this meta-analysis, temporally-integrated soil temperature data were not available. Nevertheless, all 13 N source categories will be included in a first meta-analysis of the EF1 and EF3 data from 164 field trials. To avoid temperature issue, a second meta-analysis will involve a subset of data from 132 trials for 6 N source categories including dairy cattle urine, dairy cattle dung, beef cattle dung, sheep urine, sheep dung and urea fertiliser.

5. Results

5.1 Does soil fertility affect EF3?

For the Hill Country trial where sheep and dairy cattle urine had been applied to soils, there were five replicates per plot at two slope positions across four soils (located in 3 regions). Combining replicate data to the plot level where sheep urine had been applied (n = 8) and subjecting these data to linear regression analysis, the resulting slope (0.025), offset (-0.310) and R^2 (0.564) were virtually identical to the values that had been reported by de Klein et al. (2011). We then analysed replicate level data for sheep and dairy cattle urine that had been applied to the so-called lower slope position across four soils. Linear regression analysis of these 40 data pairs yielded a slope of 0.034, offset of -0.506 and R^2 of 0.436. For these data, the largest and smallest EF3 values were 2.51 and -0.21%, respectively, and the corresponding Olsen P levels were 35 and 39 mg/kg. These data were outliers and came from replicates at Whatawhata where sheep urine had been applied to the freely drained soil at a rate of 263 kg N/ha on 23 September 2009. Therefore, these two data pairs were excluded from further data analysis. For the remaining 38 data pairs, the largest and smallest EF3 values were 2.21 and 0.02%, respectively, and the corresponding Olsen P levels were 65 and 18 mg/kg, from replicates at Ballantrae where sheep urine had been applied to the freely and poorly drained soils, respectively, at rates of 504 and 464 kg N/ha, respectively, on 22 September 2009. Linear regression analysis of the remaining 38 data pairs yielded similar values of the slope (0.035) and offset (-0.506), and an R^2 of 0.600. Strictly, the two values of R^2 of 0.436 and 0.600 should not be compared because the former had a sample size of 38, while the later had 40. Further, logarithmic transformation of the 38 data pairs and linear regression analysis yielded a power function which was shown to be superior. This curvilinear relation accounted for 67% of variability in the logarithm of dairy cattle and sheep urine EF3 (R^2 = 0.67). This relation may be written as EF3 = 2.38×10^{-5}*Olsen $P^{2.78}$ where EF3 has been expressed in % units, Olsen P in units of mg/kg of soil and standard errors of the multiplier term and power coefficient were 2.52×10^{-6} and 0.33, respectively (Figure 1). This relation looks promising and warrants further research. Unfortunately, the Olsen P level in soils has not been measured in other field trials, so further data analyses were not possible. In future, Olsen P should be measured in field trial plots. There could also be merit in subjecting field trial plot soil samples to anaerobic incubation in the laboratory and measuring the N mineralisation rate, called the "available N" by commercial laboratories.

Figure 1 Relation between Olsen phosphorus (P) level in four soils (0 – 7.5 cm depth) and the nitrous oxide emission factor (EF3) for sheep and dairy cattle urine (open and closed symbols, respectively) applied to low slope positions during hill country field trials conducted in three regions. While the two panels portray the same data and fitted curve, the upper panel uses logarithmic X and Y axis scales, while the lower does not. These replicate-level data and the fitted curve have been described in the text would be useful to put equations and se on graphs -put log scale on vertical axis title would be useful to have both axis start from 0.



5.2 Was rainfall during the first month of field trials typical?

A question posed by this section's heading was the basis for a rainfall data analysis which was separate from the meta-analysis. For 115 of the 132 EF3 and EF1 field measurement trials, rainfall measurements were provided for data analysis. For 8 trials, measured rainfall during the first 30 days was significantly greater than the long-term monthly mean ($p < 0.05$). One trial involved dairy cattle urine applied to a Templeton silt loam soil on 29 April 2010 at Lincoln when rainfall during the first 30 days was 155 mm, while a long-term mean for May was 64 mm. The others involved sheep urine applied to hill country soils, three at Ballantrae, two at the nearby Awahou site and two at Whatawhata near Hamilton. One Ballantrae trial began 19 October 2005 and rainfall during the first 30 days was 344 mm, while a long-term mean for November was 91 mm. The other six trials began during the third week in September 2009. At Ballantrae and Whatawhata, rainfall during the first 30 days was 257 and 293 mm, respectively, while corresponding long-term means for October were 113 and 137 mm. this would be useful in a table.

For 35 trials, measured rainfall during the first 30 days was significantly less than a long-term monthly mean (Table 1). For 15 of these trials involving dairy cattle urine applied to soils, 12 occurred during the 3 most recent years of 2008 – 2010 (Appendix). Fifteen other trials involved dairy cattle, beef cattle and sheep dung applied to soils with 3 occurring in 2009, the rest during 2008 (Appendix). Overall, for 17 trials, rainfall during the first 30 days exceeded 50 mm. In contrast, rainfall during the first 30 days was less than 30 mm for 6 trials, while for 12 trials, it was 30 – 40 mm.

Rainfall determines soil water content and, as an approximation for pastoral soils, water storage capacity would be of order 30 mm in the uppermost 100 mm. This depth of soil can be postulated to determine N_2O emission rate from the surface. Soil water content is also affected by the evaporation rate, and a daily mean for well-watered pasture is 2.5 mm. Dividing the soil water storage capacity by the mean daily evaporation rate, soil water supply could meet atmospheric demand for evaporation for 12 days (= 30/2.5). According to the rainfall data, 30 mm or more can be expected during the trial's first 30 days. As shown, this rainfall should prevent a soil water deficit for another 12 days. On this basis, to prevent soil water deficit that might affect EF1 and EF3, a minimum monthly rainfall requirement of 30 mm can be postulated. As stated, it was rare for rainfall to be less than 30 mm during the first 30 days of field trials where EF1 and EF3 have been measured.

Table 1 – The number of EF1 and EF3 field measurement trials when measured rainfall during the first 30 days was significantly less than a long-term monthly mean ($p < 0.05$ and denoted typical). Although there were 61 and 19 trials where dairy cattle urine and urea fertiliser were applied to soils, rainfall measurements were not provided for 15 and 2 of these trials, respectively.

Nitrogen source	Total number of trials	Number of trials when rainfall during first 30 days was significantly less than typical
Dairy cattle urine	46	15
Dairy cattle dung	18	7
Beef cattle dung	4	2
Sheep urine	16	1
Sheep dung	14	6
Urea fertiliser	17	4

5.3 N_2O emission factors (EF3 and EF1) for the inventory

5.3.1 Preliminary data analyses

Our primary focus will be 6 N source categories including dairy cattle urine, dairy cattle dung, beef cattle dung, sheep urine, sheep dung and urea fertiliser. There were 132 sets of data for these six N source categories. For illustration, we calculated "raw" values of the mean, standard error and median (Table 2).

Table 2 Calculated "raw" values of the mean, standard error and median for six sets of EF3 and EF1 data from field measurement trials that had different N sources.

N source	Number of trials	Mean ± Standard error (SE)	Median
		%	%
Dairy cattle urine	61	1.14 ± 0.14	0.73
Dairy cattle dung	18	0.16 ± 0.04	0.13
Beef cattle dung	4	0.02 ± 0.01	0.01
Sheep urine	16	0.34 ± 0.11	0.18
Sheep dung	14	0.01 ± 0.02	0.01
Urea fertiliser	19	1.07 ± 0.43	0.29

The raw means take no account of some trials having been conducted under different conditions. Further, some comparisons might be better than others such as different N sources compared during the same trial at the same site. As an example, if we had treatments A and B at one site both with values of 1 and treatment A at another site with a value of 0.5, the raw mean for treatment A would be 0.75, while the raw mean for treatment B would be 1. For this situation, the evidence of a difference between treatments A and B could be confounded by the possibility that conditions at the second site have caused the lower value. By meta-analysis, one can attempt to account for such situations. However, this can be challenging because often the data have not been collected in a pre-planned way for such purposes.

The raw means and accompanying medians are generally different and by different degrees. This indicates the data in a set are skewed, and not representative of a normal frequency distribution portrayed by a symmetrical, bell-shaped curve. This situation dictated a need for data transformation to ensure that the analysis assumptions of constant variance and approximate normality (of the residuals) were met. We have used log transformation with a constant added before taking logs. As stated, for each trial and N source, we have calculated mean values for EF1 or EF3 as (mean of treated reps – mean of control reps)/N applied and corresponding medians. Based on inspection of these data and residuals, a constant of 0.05 was appropriate, so this was used. A larger value of the constant was found to have "pushed up" the lower values too much. The small value of the constant reflected that the data had been "smoothed" by the calculation of means and medians for each trial and N source. Preliminary meta-analyses of the EF1 and EF3 data using means or medians yielded essentially the same results, so only results based on the means will be given in this report.

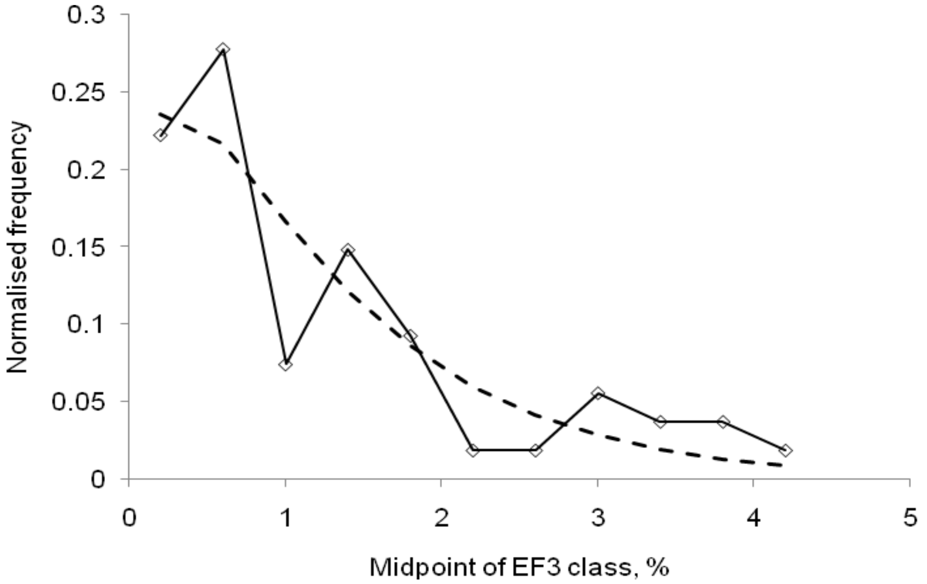
The subset of data containing the largest number of trials would be dairy cattle urine. While Table 2 indicates a total of 61 trials, there have been 54 trials where dairy cattle urine has been applied to lowland soils, involving 13 soils from 6 regions including Waikato, Manawatu, Canterbury, West Coast, Otago and Southland. The trials have been conducted at 7 experimental sites located from Ruakura, in Hamilton, southwards to Tussock Creek, located near Invercargill. The first and 54^{th} trials began 11 May 2000 and 18 May 2010, respectively. Means and variability statistics have been calculated from the progressively increasing number of trials (n). These data are variable as the standard deviation (SD, Table 1) is about the same size as the mean. Over time, as n increased from 13 to 23 to 34 and 54, the mean has been stable and the standard error (SE = SD/√n), a population-level uncertainty measure for the inventory, has reduced as expected according to (1/√n). To normalise, the SE can be expressed as a fraction of the mean, computing the Fractional Standard Error (FSE). FSE declined from 0.24 to 0.12 as n increased from 13 to 54. **Thus, by conducting 4 times as many trials, the estimate of EF3 uncertainty has been halved, in accordance with statistical theory.**

Table 3 Calculated "raw" statistics for the dairy cattle urine EF3 (%) data, calculated prior to transformation for further data analysis, for selected periods until the completion of 54 field trials on 22 November 2010.

Period	Number of trials, n	Mean EF3 (%)	Standard deviation, SD	Standard error, SE= SD/√n	FSE, SE as a fraction of the mean
11 May 2000 – 6 October 2003	13	1.20	1.03	0.29	0.24
11 May 2000 – 18 August 2005	23	1.25	1.18	0.25	0.19
11 May 2000 – 4 November 2008	35	1.28	1.17	0.20	0.15
11 May 2000 – 22 November 2010	54	1.25	1.09	0.15	0.12

For all data from the 54 trials, a median was 0.85%, a value less than the mean. Thus, half these data had a value less than 0.85% as illustrated by the frequency distribution in Figure 2. Further, the mean (1.25%) minus the minimum value (0.02%) was 1.23%, while the maximum value (4.28%) minus the mean was 3.03%. Thus, the frequency distribution of these data was skewed with respect to a “normal” distribution whereby the mean would be located exactly in the middle of a symmetrical bell-shaped curve. A skewed frequency distribution of EF3 data may be interpreted to be a consequence of a bounded lower limit close to zero, acknowledging the rare occurrence of negative values that were not present in this subset of the data, while the upper limit can be considered unbounded. For valid statistical tests, these data will require transformation so that residuals from the model are approximately normally distributed.

Figure 2 Frequency distribution of the dairy cattle urine EF3 data (normalised for the 54 trials, so an integrated area under the data would be 1) portrayed according to 0.4% classes. The dashed curve is a gamma distribution that has been fitted to these data including alpha and beta parameters that were 1.30 and 0.96, respectively, determined by combinations of the mean and SD.



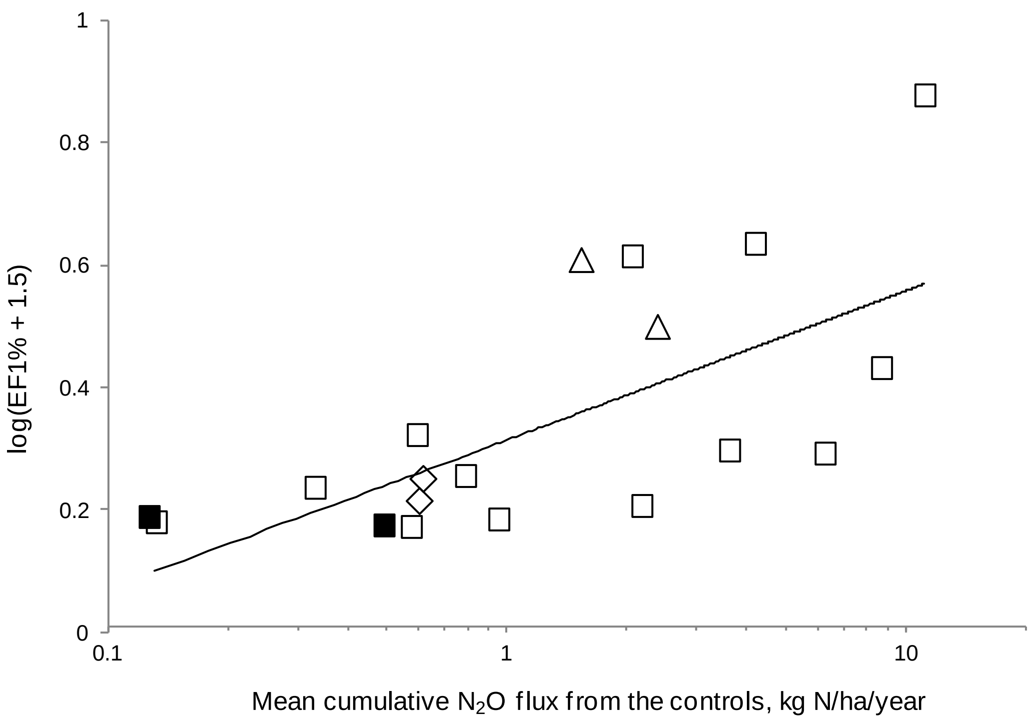
The subset of EF1 data, when urea fertiliser had been applied to soils, was the most variable and had the greatest difference between the raw mean and median values. This subset included 19 field trials. To further examine the variability of this subset, raw means of EF1 from each trial are shown in Table 4, and 95% confidence intervals have been calculated on the basis of a standard error of the difference between the urea-treated and control plots. For each trial according to a t test, it was determined if the cumulative mean N_2O flux from the urea-treated plots had been significantly greater ($p < 0.05$) than the controls.

Table 4 Raw mean values of EF1 (± 95% confidence interval) from 19 field trials where nitrogen (N) in the form of urea fertiliser had been applied to half the plots, the other plots acting as untreated controls. For 11 field trials, an asterisk denotes that the cumulative mean N_2O flux from the urea-treated plots had been significantly greater ($p < 0.05$) than the controls according to a t test. For the other field trials, no asterisk indicates $p > 0.05$.

Location	Soil	Number of plots per treatment	Start of trial	Trial duration, days	N application rate, kg N/ha	EF1, %
Ruakura	Te Kowhai	12	9/6/03	30	50	0.46 ± 0.50
Ruakura	Te Kowhai	4	25/8/03	213	50	7.56 ± 14.93
Ruakura	Te Kowhai	12	20/8/03	47	50	1.21 ± 1.51
Ruakura	Te Kowhai	12	12/11/03	34	50	0.49 ± 0.38*
Ruakura	Te Kowhai	12	7/4/04	30	50	0.03 ± 0.06
Ruakura	Te Kowhai	12	30/6/04	50	50	2.63 ± 1.67*
Ruakura	Te Kowhai	12	23/11/04	40	50	0.11 ± 0.20
Ruakura	Te Kowhai	12	19/2/05	30	50	-0.01 ± 0.06
Ruakura	Te Kowhai	12	7/7/05	42	50	0.61 ± 0.18*
Ruakura	Horotiu	4	25/8/03	213	50	2.83 ± 1.68*
Ruakura	Horotiu	4	22/5/09	214	150	0.23 ± 0.14*
Massey	Poorly drained	4	4/6/09	133	50	2.57 ± 2.59*
Massey	Poorly drained	4	4/6/09	153	50	1.66 ± 2.71
Lincoln	Lismore	5	20/5/09	184	200	0.14 ± 0.13*
Lincoln	Lismore	5	21/5/09	184	100	0.29 ± 0.26*
Invermay	Wingatui	12	1/10/10	46	50	0.05 ± 0.03*
Ruakura	Horotiu	12	22/10/10	41	50	0.02 ± 0.02*
Invermay	Wingatui	6	21/1/11	60	50	0.00 ± 0.11
Ruakura	Te Kowhai	6	17/2/11	68	50	0.30 ± 0.27*

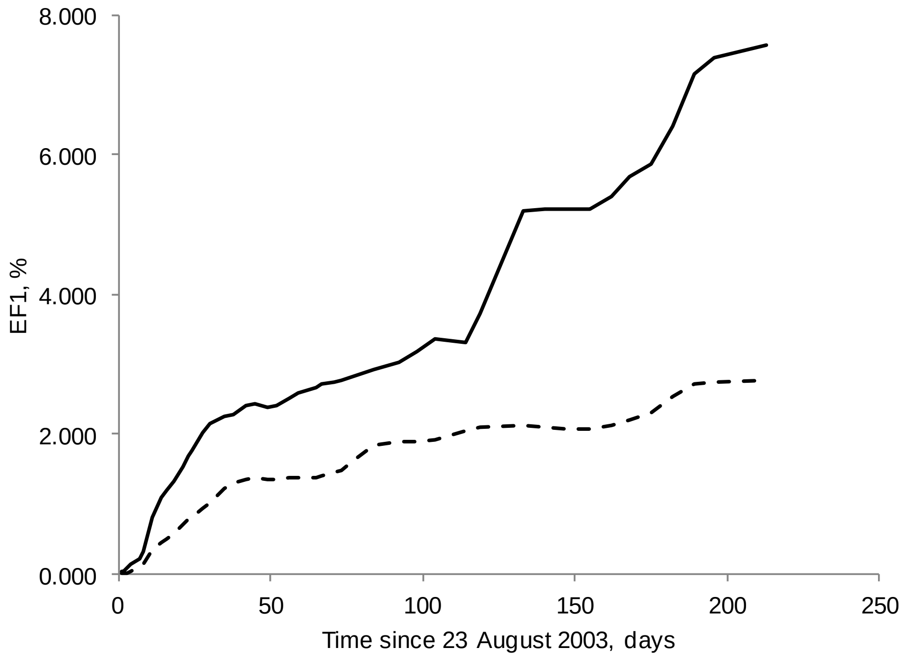
Statistical analyses have shown the EF1 data were variable. Earlier, based on statistical analysis of a subset of dairy cattle and sheep urine EF3 data from a hill country trial, we determined that EF3 depended on the soil fertility (Olsen P), accounting for 67% of the variability (Figure 2). Unfortunately, soil fertility was not measured during the 19 trials that measured EF1. However, we can postulate a proxy, cumulative mean N_2O flux from the control plots. We recognise that the calculation of EF1 involved the proxy as {(cumulative mean N_2O flux from the plots subjected to N application - cumulative mean N_2O flux from the control plots)/N application rate}. Moreover, the proxy may also be affected by trial duration, so cumulative mean N_2O flux from the control plots has been divided by the trial duration and expressed in units of kg N/ha/year. These trials have been conducted at 4 locations. Earlier, Kelliher et al. (2010) analysed sets of N_2O flux measurements made in the control plots of EF3 trials at locations which included Ruakura, Invermay and Lincoln. These were individual measurements, not cumulative values, and the mean was 1.5 ± 0.1 kg N/ha/year for Horotiu soil at Ruakura (± 95% confidence interval, n = 1,271 measurements conducted between 11 May 2000 and 9 March 2009) that was significantly greater than 0.6 ± 0.1 kg N/ha/year for Wingatui soil at Invermay (605 measurements conducted between 19 February 2002 and 16 March 2004) and 0.4 ± 0.1 kg N/ha/year for Lismore soil at Lincoln (104 measurements conducted between 9 September 2002 and 22 November 2002). For the data from 19 EF1 measurement trials, there was a significant, positive relation between mean values of EF1 and cumulative oxide N_2O flux from the control plots, accounting for 43% of variability (Figure 3). In terms of location, most of the data have come from Ruakura (and the Te Kowhai soil) and this subset accounts for much of the variability in the EF1 data set. The two values from Massey (Palmerston North) were consistent and significantly greater than the two consistent values from Lincoln. The two EF1 values from Invermay were also consistent, and cumulative oxide N_2O flux from the control plots were both small but different from one another. The data from Ruakura demonstrate EF1 can be wide ranging at a given location. There have been relatively few measurements at other sites, but these data have suggested EF1 can also vary from one soil to another. The limited range of locations and soils that have been subjected to EF1 measurement will make it challenging for the meta-analysis.

Figure 3 Relation between mean cumulative nitrous oxide (N_2O) flux from the controls and the nitrous oxide emission factor for urea fertiliser applied to soils (EF1) during 19 field trials conducted at 4 locations (Ruakura, open squares; Invermay, solid squares; Massey, open triangles; Lincoln, open diamonds). The mean EF1 data have been transformed to ensure that the regression analysis assumptions of constant variance and approximate normality (of the residuals) were met. We used log (base 10) transformation with a constant of 1.5 added before taking logs in order to calculate log(EF1% + 1.5) shown on the Y axis. Regression analysis accounted for 43% of variability (R^2 = 0.43) according to the line, log(EF1% + 1.5) = 0.106 ln(N_2O flux) + 0.313. The graph uses a logarithmic X axis scale.



The set of EF1 raw means varied from a minimum of -0.01 up to a maximum of 7.56%. The maximum value was exceptional, warranting further examination. As for all data, it was determined that no errors of GC calibration or computation had been made during the trial yielding a raw mean EF1 of 7.56%. Further, the 4 plots that had been subjected to urea fertiliser application generally yielded broadly similar N_2O fluxes throughout the trial, similarly for the control plots. This trial was one of the longest that has been undertaken. For the Te Kowhai soil, EF1 increased steadily and significantly throughout the trial, while for the nearby Horotiu soil, EF1 obtained 66% of its final value (on day 213) within 84 days (versus 39% for the Te Kowhai soil, Figure 4). The application of isotopically labelled urea ^{15}N to soils has shown approximately 80% of N_2O emissions can be derived from the applied N, while the remainder, 20%, derived from N sourced from the soil's organic matter, an N application priming effect according to Taghizadeh-Toosi et al. (2011, see their Figure 6). On this basis, we would deduce that the Te Kowhai soil plots that had been subjected to urea fertiliser application had on-going elevated N_2O emissions that should mostly be attributed to this treatment and accounting for EF1 increasing over the trial. The Te Kowhai soil has another attribute that may also account for its emissions responding differently to that of the Horotiu soil. The Te Kowhai soil is poorly drained, so that following prolonged rainfall, the water content of this soil can increase significantly and more so than for a freely draining Horotiu soil. Following N application, N_2O emissions can be very responsive to soil water content. For example, Van der Weerden et al. (2011) reported that increasing the volumetric soil water content by 0.10 m^3 water m^{-3} soil corresponded with an approximately 100-fold increase in N_2O emissions. For the Te Kowhai soil, but not the Horotiu soil, rainfall stimulated the second and third episodes of EF1 increasing sharply. Considering the data in Table 4, further EF1 measurement trials on a greater range of soils and conditions seems warranted.

Figure 4 Mean EF1 values for the Horotiu and Te Kowhai soils at Ruakura during 23/8/03 – 25/3/04. During days 114 - 133 (17/12/03 - 4/1/04) and 155 – 213 (27/1/04 – 25/3/04), drought-breaking rain stimulated N_2O emissions from the poorly-drained Te Kowhai soil (solid line, final EF1 = 7.56%), but not from the freely-drained Horotiu soil (dashed line, final EF1 = 2.83%).



To better understand the nature of all 6 sets of data, we have done a series of classifications. A first classification was according to the trial site's topographic type on the basis of lowland versus hill country sites, specified by the researchers including hill country sites that had low slope positions < 12° (Table 5). For context, earlier, across NZ, grazed pasture area was classified according to the land's dominant slope as < 15º called lowland and the rest hill country (Dr Andrew Manderson, pers. comm.). This distinction reflected the different animals and farming intensity, the latter commonly involving significantly greater stocking density and fertiliser application. The lowland area was 5.9 M ha, equally split between the N and S islands. Lowland dairy farms are the most intensive with ~1.5 M ha of grazed area countrywide during the milking season. Another ~0.7 M ha supports these farms with supplemental feed production and the provision of winter grazing areas. Some cattle from dairy farms become involved in beef production. For beef cattle and sheep, there are intensive lowland fattening and finishing farms but mostly, these animals extensively graze the hill country (5.2 M ha with 56% located in the N Island).

Table 5 Number of EF1 and EF3 field measurement trials that have been conducted at lowland and hill country sites for five N sources. This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Lowland	Hill country
Dairy cattle urine	53	8
Dairy cattle dung	18	0
Sheep urine	4	12
Sheep dung	4	10
Urea fertiliser	19	0

For trials at lowland sites, the N sources were generally dairy cattle excreta (urine and dung) and urea fertiliser. The sheep urine and dung trials have generally been conducted at hill country sites. All 4 of the beef cattle dung trials included in the meta-analysis were conducted at hill country sites.

A second classification was according to the soil's drainage class (freely versus poorly drained soils, Table 6).

Table 6 Number of EF1 and EF3 field measurement trials that have been conducted on freely and poor-drained soils for five N sources. This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Freely drained soils	Poorly drained soils
Dairy cattle urine	29	32
Dairy cattle dung	8	10
Sheep urine	8	8
Sheep dung	7	7
Urea fertiliser	7	12

For all N sources, about half the trials have been conducted on freely-drained soils. Across NZ, where pastoral agriculture has been practiced, including tussock grassland, it has been estimated that 74 and 9% of the land area has freely- and poorly-drained soils, respectively (Sherlock et al., 2001). The remaining 17% of land area has imperfectly-drained soils which can become poorly drained if rainfall is sufficient.

A third classification was made according to season (Table 7). As stated, a season was defined by the 15th day of each trial as a month. The month became a season according to groups as 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.

Table 7 Number of EF1 and EF3 field measurement trials that began each season for five N sources. This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Autumn	Winter	Spring	Summer
Dairy cattle urine	21	18	21	1
Dairy cattle dung	1	8	9	0
Sheep urine	0	0	16	0
Sheep dung	0	6	8	0
Urea fertiliser	3	8	6	2

As stated earlier, the largest number of trials has been conducted with dairy cattle urine with about one-third of the trials having their first month during autumn, winter and spring, but only 1 trial with its first month during summer. There have been only 2 other trials whose first month occurred during summer, both with urea fertiliser. There have also been only 4 other trials whose first month occurred during autumn, 1 with dairy cattle dung and 3 with urea fertiliser. There have been 22 and 39 other trials whose first month occurred during winter and spring, respectively. For the meta-analysis, these uneven seasonal distributions of the trials contributed to the challenge of determining a seasonal effect on EF1 and EF3.

A fourth classification was made according to the rainfall ratio, a ratio of measured rainfall during the first 30 days of a trial relative to a typical monthly rainfall from the closest weather station, determined as described earlier (Table 8). As stated, for the meta-analysis, in order not to pre-suppose a relation between the rainfall ratio and EF3 and EF1, the rainfall ratio was grouped into 4 levels; namely, ratio < 0.5, $0.5 <$ ratio ≤ 1.0, $1.0 <$ ratio ≤ 2.0 and ratio > 2.0.

Table 8 Number of EF1 and EF3 field measurement trials classified by a rainfall ratio, measured rainfall during the trial's first 30 days divided by the typical monthly rainfall, for five N sources (see text for further explanation). Also shown are the number of trials for which measured rainfall was not supplied by the researchers, denoted missing data. This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Rainfall ratio < 0.5	0.5 < rainfall ratio ≤ 1.0	1.0 < rainfall ratio ≤ 2.0	Rainfall ratio > 2.0	Missing data
Dairy cattle urine	6	16	17	7	15
Dairy cattle dung	3	7	2	0	6
Sheep urine	1	2	2	7	4
Sheep dung	0	8	4	0	2
Urea fertiliser	4	5	8	0	2

For a total of 29 trials, rainfall data had not been provided by researchers. Thus, the total number of trials with rainfall ratio data for the meta-analysis was 99 of which 24 and 14% had a rainfall ratio < 0.5 and > 2.0, respectively. If for the purpose of classification, not meta-analysis, a rainfall ratio between 0.5 and 2.0 was a range that could be considered "typical", 62% of the trials could be considered "typical".

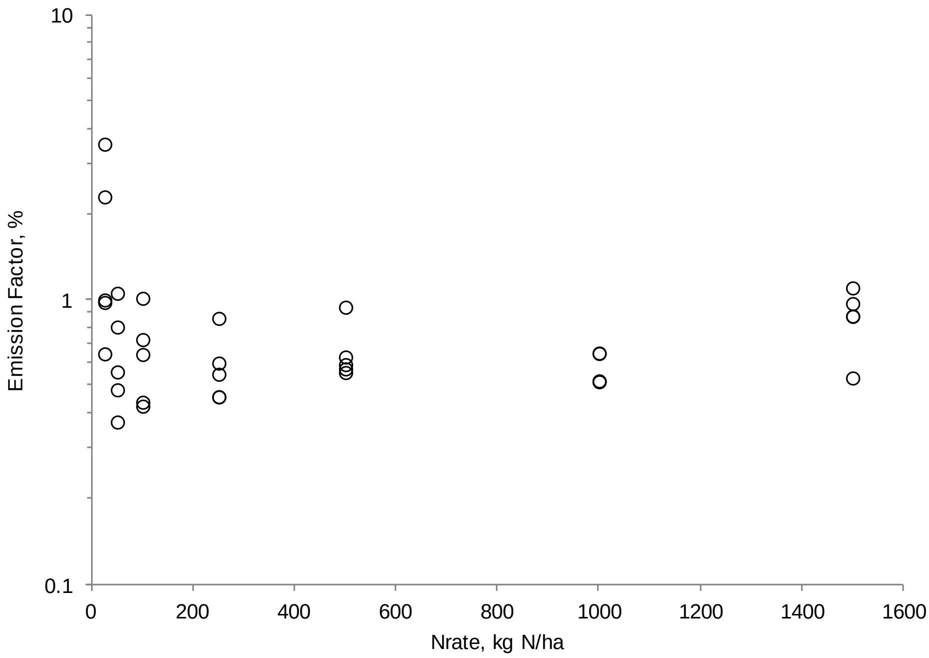
A fifth classification was according to the N application rate (Table 9).

Table 9 Number of EF1 and EF3 field measurement trials classified by the N application rate to soils, denoted Nrate and represented by 100 kg N/ha classes. This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Dairy cattle urine	Dairy cattle dung	Sheep urine	Sheep dung	Urea fertiliser
Nrate, kg N/ha					
0 – 100	0	0	2	0	17
101 – 200	0	0	2	0	2
201 – 300	0	0	8	6	0
301 – 400	0	0	2	6	0
401 – 500	14	0	1	2	0
501 – 600	20	0	1	0	0
601 – 700	7	0	0	0	0
701 – 800	1	0	0	0	0
801 – 900	0	2	0	0	0
901 – 1000	19	4	0	0	0
1001 – 1100	0	6	0	0	0
1101 – 1200	0	5	0	0	0
1201 – 1300	0	0	0	0	0
1301 – 1400	0	1	0	0	0
Total	61	18	16	14	19

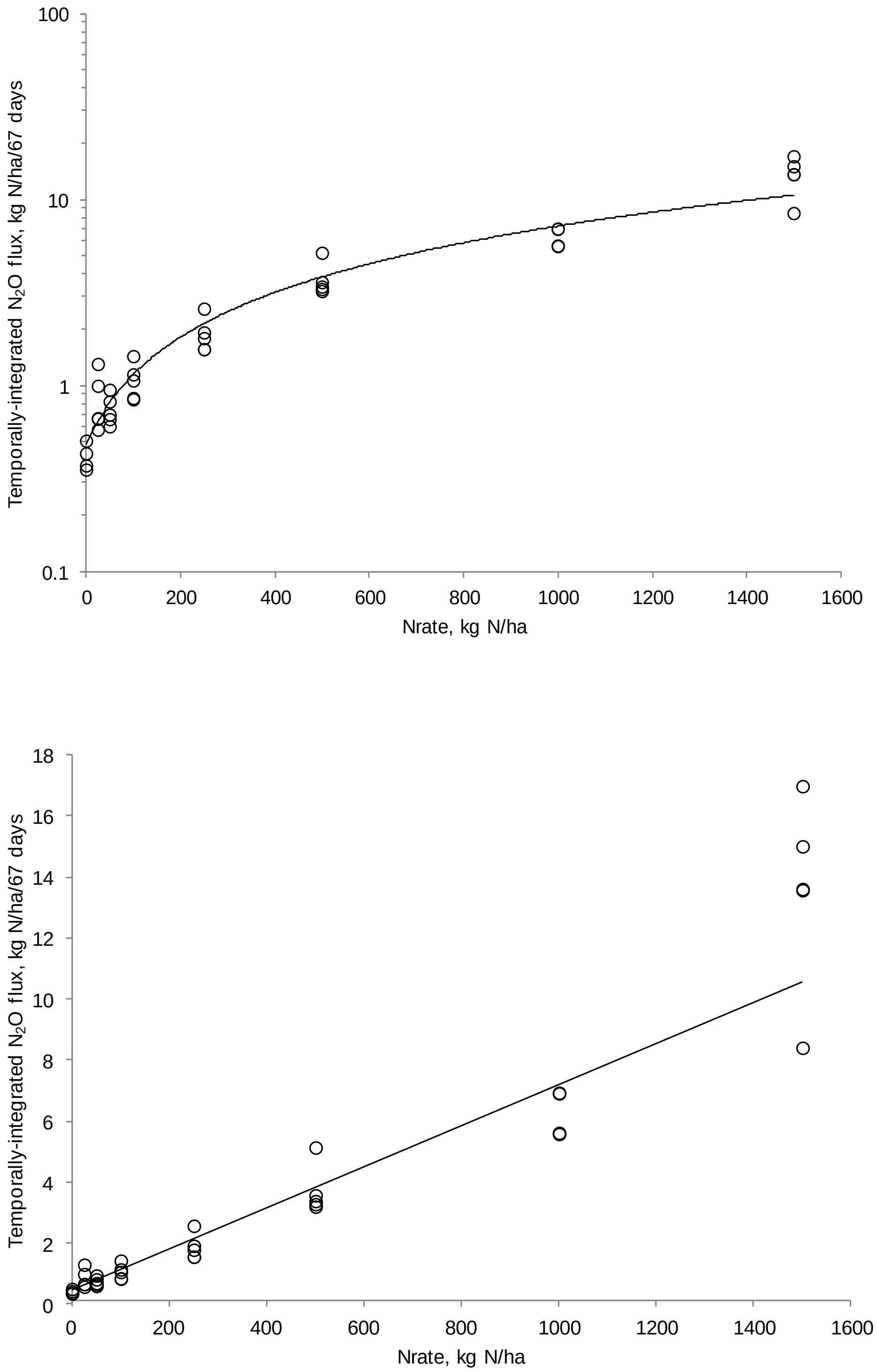
For urea fertiliser, 17 trials had an N application rate of 50 kg N/ha, while 3 others had 100, 150 and 200 kg N/ha. In contrast, for dairy cattle dung, the N application rate ranged from 900 - 1390 kg N/ha. The widest range of N application rate for an N source category was 436 – 1000 kg N/ha for dairy cattle urine. To proceed, we postulate there would be no effect of the N application rate on EF1 and EF3. Unfortunately, this hypothesis creates a problematic situation because an EF includes the N application rate as its denominator. Nevertheless, our hypothesis was independently tested using unpublished experimental data (Li and Kelliher, unpublished). In this study, topsoil was sampled at a dairy farm at Lincoln and returned to the laboratory. The form of N applied was aqueous urea solution at application rate of 25 – 1500 kg N/ha. The samples were incubated in a laboratory for 68 days under constantly warm and wet conditions. This study did not include pasture plants growing in the soil. During the study, at regular intervals, direct N_2O fluxes measured by a chamber method. The fluxes were temporally integrated, and then divided by the N application rate in order to compute emission factors. The emissions factors were plotted against the corresponding N application rate (Figure 5). On this basis, there was no evidence for an effect of N application rate on the emission factor, though there was much more scatter of the emission factor data at 25 kg N/ha.

Figure 5 Relation between an aqueous urea solution N_2O emission factor (%) and the N application rate (Nrate, kg N/ha) for soil samples from a dairy farm at Lincoln which were incubated for 67 days in the laboratory under warm and wet conditions and subjected to regular N_2O emissions measurements by a chamber method. The Y axis scale is logarithmic.



To avoid the interdependence situation created by plotting emission factor data against the N application rate, we changed the dependent variable to the temporally-integrated N_2O fluxes (Figure 6). To test our hypothesis, these data were analysed to determine if they could be described by a linear relation, the slope yielding a mean EF. Alternatively, a curvilinear relation would be evidence for rejecting the hypothesis because the relation's slope would be dependent on the N application rate.

Figure 6 Relation between the N application rate (Nrate, kg N/ha) and temporally-integrated, replicate values of N_2O flux for soil samples from a dairy farm at Lincoln that were incubated for 67 days in the laboratory under warm and wet conditions. While the two panels portray the same data and line, the upper panel uses a logarithmic Y axis scale, while the lower does not. Assuming multiplicative or proportional errors, regression analysis yielded a linear relation, N_2O flux = [$6.72 \times 10^{-3} \pm 4.51 \times 10^{-4}$] * Nrate + 0.48 ± 0.04, accounting for 95% of the deviance. On this basis, the relation's slope would be this experiment's estimate of a mean EF, 0.67 ± 0.05%.



On the basis of this hypothesis test (Figures 5 and 6), we proceeded with the meta-analysis on the basis that there should be no effect of the N application rate on EF1 and EF3. However, we acknowledge that further research is warranted under field conditions with soils populated by growing pasture plants.

A sixth classification was according to the year when a field trial began (Table 10).

Table 10 Number of EF1 and EF3 field measurement trials that have been conducted in 2 year classes with year determined by that on the trial's first day. This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Dairy cattle urine	Dairy cattle dung	Sheep urine	Sheep dung	Urea fertiliser
Year					
1999 - 2000	2	0	0	0	0
2001 - 2002	9	4	2	2	0
2003 – 2004	9	2	2	0	8
2005 – 2006	2	0	4	0	2
2007 – 2008	20	8	0	12	0
2009 – 2010	19	4	8	0	7
2011	0	0	0	0	2
Total	61	18	16	14	19

Overall, 53% of the trials have been conducted during the past 5 years. However, the corresponding value was 86% for sheep dung and 67% for dairy cattle dung. For beef cattle dung as an N source, there have been only 4 trials, all conducted during 2008. These different distributions reflect the development of EF1 and EF3 research, governed by the available funding and knowledge over time. This began with a decision by researchers and policy analysts at the end of 1999 that the first priority for field measurement trials should be dairy cattle urine EF3 for soils at lowland sites, anticipated to be the most influential variable in NZ's agricultural soils N_2O emissions inventory, later demonstrated by an inventory uncertainty assessment (Kelliher et al. 2004). Further, until 5 years ago, nearly all of the trials had been conducted at lowland sites. However, and importantly, throughout the 11 year period of trials generating data for this meta-analysis, similar soil chamber and gas sampling methods have been used to measure direct N_2O emissions after N had been applied to soils. Moreover, the vast majority of these gas samples have been analysed in the same laboratory.

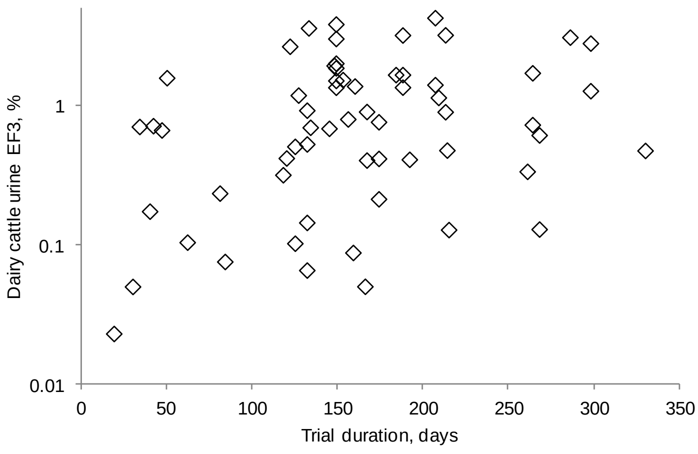
A seventh, and final, classification was made according to trial duration (Table 11).

Table 11 Number of EF1 and EF3 field measurement trials classified by their duration, represented by 30 day classes. A trial's duration was determined by the period, after soils received an N application, during which there was significantly greater direct N_2O emissions from treated areas than the controls ($p < 0.05$). This table does not include 4 trials where beef cattle dung was applied to soils.

N source	Dairy cattle urine	Dairy cattle dung	Sheep urine	Sheep dung	Urea fertiliser
Days					
0 – 30	2	0	0	0	3
31 – 60	5	0	4	0	8
61 – 90	3	0	5	0	1
91 – 120	2	0	0	0	0
121 – 150	18	4	3	6	1
151 – 180	10	6	0	6	1
181 – 210	8	3	2	0	2
211 – 240	4	1	0	0	3
241 – 270	5	1	0	0	0
271 – 300	3	2	2	2	0
301 – 330	1	1	0	0	0
Total	61	18	16	14	19

Overall, 74% of the field trials lasted longer than 120 days. In contrast, and exceptional, the corresponding value was only 37% for urea fertiliser. Data can be analysed to determine if trial duration has affected EF1 and EF3. For 61 trials where dairy cattle urine had been applied to soils, we plotted EF3 against trial duration and regression did not account for a significant portion of the variability (Figure 7). Thus, trial duration should not affect EF1 and EF3.

Figure 7 Relation between dairy cattle urine EF3 and trial duration for 61 field measurement trials. The Y axis scale is logarithmic.



For the 6 primary N sources, the mean trial duration was 152 days (± 75 days, standard deviation, n = 132). During a trial, on average, the N_2O fluxes had been measured on 30.4 ± 13.4 occasions (days). Combining, on average, we can calculate the N_2O fluxes were measured at 5 day intervals.

For the first 21 – 30 days after N application to soils, when N_2O fluxes were usually greatest, gas sampling would have been done at 2 – 3 days intervals. Afterwards, gas sampling was usually done at 7 – 14 day intervals.

5.3.2 Meta-analysis

As stated, this data analysis used mean values across the replicates in each trial. For both meta-analyses, including EF3 and EF1 data from 164 trials and 13 N source categories and from 132 trials and 6 N source categories, the only effect that was statistically significant ($p < 0.05$) was N source. The other effects were not significant ($p > 0.05$) including topographic type (lowland versus hill country), soil drainage class (freely versus poorly drained), season and rainfall (ratio of rainfall during the first 30 days relative to a typical monthly rainfall). To estimate means for each N source, best linear unbiased predictors (BLUP) were calculated. To get these, the fixed effects were treated as random, so the more poorly estimated means were "shrunk" towards a data set's (N source's) overall mean. On these bases, BLUP estimates would be considered superior to the earlier, "raw" calculations. BLUPs for each N source are back-transformed, bias-corrected mean values of EF3 and EF1 as well as the associated lower and upper values of the SE. The two meta-analyses yielded very similar mean values and standard errors for the 6 N sources of primary interest for this report, indicating the robustness of this approach (Table 12).

The BLUP estimates (Table 12 and Figure 8) would be recommended for the inventory. The BLUP-estimated mean values for dairy cattle urine EF3 and sheep urine EF3 were not significantly different ($p > 0.05$, for 95% confidence about the mean, ± twice the SE). These outcomes support the NZ agricultural soils N_2O emissions inventory's current value of 1% for dairy cattle and sheep urine EF3. The BLUP-estimated mean values for dairy cattle urine and dung EF3 were significantly different ($p < 0.05$). While the estimated values of dairy and beef cattle dung EF3 were quite different, the difference was not statistically significant ($p > 0.05$), attributable to the relatively large values of SE for beef cattle dung EF3. This reflects the small number of beef cattle dung EF3 measurement trials (n = 4). For sheep, the BLUP-estimated mean values for urine and dung EF3 were also significantly different ($p < 0.05$). There were relatively large values of SE for sheep urine and dung EF3 based on a relatively small number of trials. These results support the earlier recommendation to disaggregate EF3 for urine and dung (Luo et al., 2010), with suggested values of 1% and 0.25%, respectively, not significantly different ($p > 0.05$) to those determined by the meta-analysis reported here. The BLUP-estimated mean values of dairy cattle and sheep dung EF3 and urea fertiliser were not significantly different ($p > 0.05$). Dung and urea fertiliser applied to soils should not penetrate as much as urine. This could be one reason why urine has a larger EF3 than dung and urea fertiliser. We will explore this hypothesis further for urea fertiliser.

The BLUP-estimated mean value for urea fertiliser EF1 was significantly different to the corresponding EF3 values for sheep and dairy cattle urine ($p < 0.05$). This difference will be explored by examining some possible underlying processes. First, for urea fertiliser, sheep urine and dairy cattle urine, based on the data in Table 9, typical N application rates had been 50, 250 and 500 kg N/ha, respectively. Although a controlled incubation experiment indicated no effect of the N application rate on EF1 when urea had been applied in the form of an aqueous solution (Figure 5 and 6), there had been no plants growing in the soil samples. The EF1 trials were conducted on farms and the soils included pasture plants, so a portion of the applied N could have been taken up by plant, depending on uptake rate during the trial. However, plants may not affect EF1 and EF3 solely on the basis of N uptake. For example, after dairy cattle urine (590 kg N/ha) was applied to pots of soil with and without pasture plants under well-watered and illuminated conditions at 23 °C, the presence of plants corresponded with a significantly greater, cumulative N_2O flux (Uchida et al. 2011). This was interpreted to suggest plant supply of carbon (energy) had enhanced activity of the N_2O-producing microbial community and associated processes. In contrast, this study found no significant effect of the plants when the temperature was reduced to 10 °C.

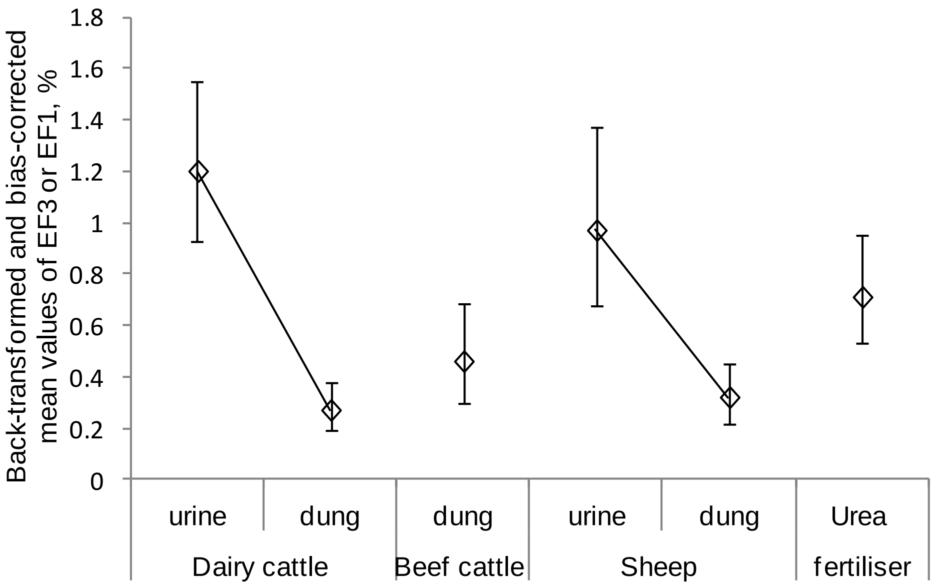
Urea fertiliser is generally applied in the form of granules onto the surface. While contact with water dissolves the granules, penetration and distribution in soils might be different to the urea in sheep and dairy cattle urine applied to soils in an aqueous solution. For context, we measured 40 granules of commercial-grade urea fertiliser and found a mean diameter of 3 mm and mass of 24 mg. Based on a granule mass of 24 mg and urea fertiliser application rate of 50 kg N/ha, it can be calculated that a mean distance between granules would be 70 mm. After applying urea fertiliser granules at 50 kg N/ha to Templeton silt loam soil beneath pasture at Lincoln, radial sampling with an 8 mm diameter micro-corer and subsequent soil pH measurements showed the pH to have been elevated by urea hydrolysis up to 24 mm from the granules (Sherlock et al. 1986). On this basis, as noted by Sherlock et al. (1986), the hemisphere of pH influence exerted by adjacent urea granules would include no overlap. Moreover, we can combine the distances of influence (24 mm) and granule spacing (70 mm) to estimate that 32% of volume
(= 100 * $\{[24 \times 2]/70\}^3$ with a factor of 2 accounting for granules being adjacent to one another) in the uppermost 24 mm depth of soil will be influenced by elevated pH following urea application at 50 kg N/ha. An elevated pH in soils will increase solubility of the organic matter, making the associated carbon (energy) more readily available to the microbial community (eg, Kelliher et al. 2005). This will include the microbes that produce N_2O and the higher pH should also enhance plant activity that, in turn, should also increase the N_2O flux as described earlier (Uchida et al. 2011).

The urea in sheep and dairy cattle urine is applied to soils as an aqueous solution. Approximate penetration calculations can be done for the sheep and dairy cattle urine applications to soils during EF3 measurement trials. For these trials, typical rates of urine application have been 5 and 10 litres/m^2, respectively (de Klein et al. 2003). These urine application rates would be equivalent to rainfall or irrigation events of 5 and 10 mm, respectively. The most common, antecedent soil water content would be the field capacity and a typical value would be 0.4 m^3/m^3. Using this information and bulk and particle densities of 1000 and 2650 kg/m^3, respectively, along with assumptions that the soil and water distribution were uniform, it can be calculated that a mean penetration depth for such sheep and dairy cattle urine applications would be 23 and 45 mm, respectively. Unlike, the effect of surface-applied urea granules affecting 32% of volume in the uppermost 24 mm depth of soil, sheep and dairy cattle urine applications should affect 100% of volume in the uppermost 23 and 45 mm depth of soil, respectively. Moreover, as for urea granules, there should be an additional depth of soil influenced by sheep and dairy cattle urine applications that might be of order 24 mm following the results of Sherlock et al. (1986). Thus, urine application should affect much more soil volume than urea fertiliser application, providing much more associated carbon (energy) to the microbial community which should increase the N_2O flux.

It has recently been reported that EF1 of a pastoral soil under field conditions did not practically or significantly differ ($p > 0.05$) when urea had been applied at a rate of 100 kg N/ha in the form of granules and ground, fine particles mixed with water (40% by weight and sprayed onto the surface, Dawar et al. 2011). Based on a granule mass of 24 mg and urea fertiliser application rate of 100 kg N/ha, it can be calculated a mean distance between approximately 3-mm-diameter granules would be 49 mm. No size information about the ground, fine particles was provided by Dawar et al. (2011), but icing sugar may be analogous, and we found a sample of icing sugar passed through a sieve with 0.355 mm sized mesh (holes), suggesting ground, fine particles of urea fertiliser might have been an order of magnitude smaller than granules. However, EF1 was evidently not affected by "particle" size and urea fertiliser distribution on the "surface" following application.

Table 12 and Figure 8 Mean values of EF3 or EF1 for 6 N sources estimated by BLUP calculations (as open diamonds in Figure 8). A bias correction accounts for known downward bias arising from transformation of the data. Also shown are the associated lower and upper standard errors, SE (as vertical bars in Figure 8). If the Y axis of Figure 8 had a logarithmic scale, the upper and lower SE would be equal.

Nitrogen source	Number of trials; lowland, hill country	Back-transformed and bias-corrected mean values of EF3 or EF1 (%)	Back-transformed lower SE	Back-transformed upper SE
Dairy cattle urine	54, 8	1.20	0.27	0.35
Dairy cattle dung	18, 0	0.27	0.08	0.11
Beef cattle dung	0, 4	0.46	0.16	0.23
Sheep urine	4, 12	0.97	0.29	0.40
Sheep dung	10, 4	0.32	0.10	0.13
Urea fertiliser	19, 0	0.69	0.19	0.25



The BLUP estimate (Table 12 and Figure 8) for EF1 is 0.7% and this value would be recommended for the inventory. This would mean reducing EF1 from 1% to 0.7%. Prior to determining the effect of this recommendation on NZ's agricultural soils N_2O emissions inventory, we will explain the inventory calculations which determine the N_2O emissions from N fertiliser applied to agricultural soils. We begin by applying 1 kg of N fertiliser to the soil surface. A fraction of the applied N, called FracGASF and equal to 0.10, will be volatilised into the atmosphere as ammonia. On this basis, 0.90 kg of applied N will be subjected to direct N_2O emissions according to the emission factor called EF1 which will be 0.01 (1%) for these illustrative calculations. Thus, the direct N_2O emissions will be 0.0141 kg N_2O according to 0.9 kg N multiplied by 0.01 and by 1.57, a molecular mass ratio of (44/28) because the molecular mass of N_2O is 44, while that of N_2 is 28. The volatilised ammonia will be re-deposited onto the soil surface and then subjected to indirect N_2O emissions according to the emission factor called EF4 which, like EF1, will be equal to 0.01. We note that EF4 also applies to indirect emissions from ammonia deposited onto the soil surface following volatilisation for excreta N applied to soils according to the same value of EF4 = 0.01. On this basis, the inventory calculation software includes only one value of EF4. Anyway, the indirect N_2O emissions from ammonia deposited onto the soil surface following ammonia volatilisation from fertiliser N applied to the soil will be 0.0016 kg N_2O according to 0.1 kg N multiplied by 0.01 and by 1.57. Another fraction of the applied N, called FracLEACH and equal to 0.07, will be leached through the soil and then subjected to indirect N_2O emissions according to the emission factor called EF5 which is equal to 0.025. This component of the indirect N_2O emissions will be 0.0028 kg N_2O according to 0.07 kg N multiplied by 0.025 and by 1.57. Adding the direct and indirect N_2O emissions yields 0.0185 kg N2O, the total N_2O emissions.

To determine the effect of reducing EF1 from 1% to 0.7% on NZ's agricultural soils N_2O emissions inventory, we have done two inventory calculations for the year 2009 by the method used for international reporting. Firstly, for the inventory which has actually been reported for the year 2009 with EF1 equal to 1%, NZ's total agricultural soils N_2O emissions were 32.0 Gg. Based on a 100-year, global warming potential of 310, it can be calculated 32.0 Gg N2O would be equivalent to 9,918 Gg CO_2-eq. For an inventory with EF1 equal to 0.7%, and no other changes, NZ's total agricultural soils N_2O emissions during 2009 would be 9,427 Gg CO_2-eq, a reduction of 491 Gg CO_2-eq. This reduction would be equal to 491,134 tonnes CO_2-eq. We have been advised that the monetary value of one tonne CO2-eq should be NZ$25 (Dr Gerald Rys, personal communication, 21 November 2011). On this basis, the monetary value of reducing NZ's total agricultural soils N_2O emissions during 2009 by 491 Gg CO_2-eq should be NZ$12,278,343.

5.4 Inventory uncertainty assessment

For agricultural soils, NZ's N_2O emissions inventory begins by determination of an N application rate. For the inventory, N will be applied to soils in two forms, excreta deposited during grazing by farmed ruminants and urea fertiliser. An emissions factor, EF, will be applied to account for a (mass) fraction of the applied N that will be emitted into the atmosphere as N_2O. This will be called a direct emissions factor. In addition, indirect emissions account for N_2O that comes from a proportion of nitrogen that volatilises as ammonia (10%), and will be re-deposited onto soils, and another accounting for that which leaches through soils (7%). To simplify, we will multiply our estimate of the direct N_2O emissions by a factor that will be determined by the value which yields the N_2O emissions (sum of the direct and indirect emissions), calculated separately by the method used for international reporting of NZ's inventory (see below). There has been no uncertainty assessment of indirect emissions, so no uncertainty will be assigned to this factor.

To represent NZ's annual inventory of direct N_2O emissions (E_{N2O}), we write a simplified equation as:

$$E_{N2O} = \{[a_n\, d\, (1/e)\, p_n\, (1 - r_n)] + u\}\, EF \quad (1)$$

where a_n is the number of animals and remaining terms are mean values including d the animal's annual energy requirement (MJ per animal per year), e the pasture (feed) energy content (MJ/kg dry matter), p_n the pasture N content, r_n the fraction of N that will be retained in an animal and u the annual mass of N fertiliser applied to pastoral soils across NZ. For analysis, data will come from the year 2009 inventory. Firstly, to determine how much N was applied to soils in the form of excreta deposited during grazing by farmed ruminants, the quantity (a_n d) will be 588 x 10^9 MJ. The values of p_n, r_n and e will be 0.035, 0.15 and 11 MJ per kg of pasture herbage dry matter, respectively. These 3 parameters do not change from one year to another. Inserting these 4 values into equation (1) yields [a_n d (1/e) p_n (1 – r_n)] = 1590 Gg N. Based on urea fertiliser sales, the corresponding value of u will be 280 Gg N. The units on the right hand side of equation (1) require conversion, from Gg N, so E_{N2O} will be expressed as Gg N_2O. This will be done by multiplication by a molecular mass ratio of (44/28) because the molecular mass of N_2O is 44, while that of N_2 is 28.

To determine a representative value of EF, weighting factors were required. Firstly, half the excreta N assumed to have come from cattle, the other half from sheep. Urine and dung N were assumed to have comprised 67 and 33% of the total, respectively. Excreta comprised 85~~1.4~~% of the total N applied to soils, while urea fertiliser comprised 15~~8.6~~%. By combining, weighting factors could be calculated. As an example, for dairy and beef cattle urine, we combine 0.50*0.67*0.85~~14~~ to calculate a weighting factor of 0.285~~73~~ (Table 13). From the means in Table12, a corresponding fractional EF value would be 0.012 (1.2% expressed as a proportion). Overall, as shown in Table 13, we calculated a weighted mean fractional EF to be 0.0080.

Table 13 – Component weighting factors and corresponding mean values of EF from Table 12 used to calculate a weighted-mean EF for equation (1).

Nitrogen source	Weighting factor	Fractional EF	Weighted mean fractional EF
Dairy and beef cattle urine	0.285~~73~~	0.0120	
Dairy and beef cattle dung	0.1~~3~~40	0.0027	
Sheep urine	0.285~~73~~	0.0097	
Sheep dung	0.1~~3~~40	0.0032	
Urea fertiliser	0.150~~86~~	0.0069	
Weighted mean fractional EF			0.0080

We have now determined the values required to make an estimate of NZ's agricultural soils direct N_2O emissions inventory according to equation (1). To re-iterate, we insert the values for [a_n d (1/e) p_n (1 – r_n)] (= 1590 Gg N) and u (= 280 Gg N) into equation (1), multiply by the weighted mean fractional EF (= 0.008) and by 1.57 to obtain 23.5 Gg N_2O. As stated, this is an estimate of the direct N_2O emissions. To complete the calculation of total N_2O emissions from NZ's agricultural soils during 2009, we need to include the indirect N_2O emissions. By the method used for international reporting of NZ's inventory, we separately calculated the total N_2O emissions from agricultural soils during 2009 to be 32.0 Gg N_2O. Thus, a ratio of the total and direct N_2O emissions from agricultural soils during 2009 was 1.36 (= 32.0/23.5). On this basis, we will multiply our estimate of direct N_2O emissions from agricultural soils during 2009 by a factor of 1.36 to determine the total N_2O emissions from agricultural soils.

As stated, the terms in equation (1) are mean values based on sets of imperfect measurements or judgements. The uncertainty of each value will be quantified by the fractional standard error (FSE, Tables 14 and 15). As an example, for term d, the notation will be FSE[d] = SE[d]/μ_d where μ_d follows an explicit notation to denote the mean value of d. To determine FSE[EF], the weighting factors will be used again as well as FSE values for each nitrogen source. As an example, the FSE for dairy cattle urine data will be calculated using the data reported in Table 12 as [(0.27 + 0.35)/2]/1.20 to obtain 0.258 (Table 14).

Table 14 – Component weighting factors and fractional standard errors (FSE) used to calculate a weighted-mean FSE for term EF in equation (1).

Nitrogen source	Weighting factor	FSE	Weighted mean FSE
Dairy and beef cattle urine	0.285~~73~~	0.258	
Dairy and beef cattle dung	0.1~~3~~40	0.352	
Sheep urine	0.2~~73~~85	0.356	
Sheep dung	0.1~~3~~40	0.359	
Urea fertiliser	0.150~~86~~	0.312	
Weighted mean FSE			0.321

Table 15 - Fractional standard errors (FSE) for terms in equation (1) and the estimation method. The values of FSE were inserted into equation (2) to estimate FSE for the inventory as explained in the text.

Term in equation (1)	FSE	Method used to estimate FSE
a_n	0.02	Statistics NZ (Kelliher et al. 2007)
D	0.05	Expert judgement (Kelliher et al. 2007)
E	0.05	Expert judgement (Kelliher et al. 2007)
p_n	0.01	Expert judgement (Ledgard et al. 2002)
r_n	0.05	Expert judgement
U	0.03	Expert judgement (Hilton Furness, pers. comm.)
EF	0.32	Statistical analysis of the data in Tables 12 + 14

As a first uncertainty assessment of E_{N2O}, we will estimate FSE[E_{N2O}] assuming independence of the terms in equation (1). For this purpose, we will define an excreta factor called x as

$$x = a_n\ d\ (1/e)\ p_n\ (1 - r_n) \quad (2)$$

This means we can re-write equation (1) as

$$E_{N2O} = (x + u)\ EF \quad (3)$$

We can also determine FSE[x] by a root-mean-square approach, recognizing the mathematical operation involving term r_n, as

$$FSE[x]^2 = FSE[a_n]^2 + FSE[d]^2 + FSE[e]^2 + FSE[p_n]^2 + \{FSE[r_n](r_n/(1 - r_n))\}^2 \quad (4)$$

where we have written $FSE[x]^2$ to denote $(FSE[x])^2$. Combining equations (3) and (4), we can write the following approximation

$$FSE[E_{N2O}] \approx \{((x^2\, FSE[x]^2 + u^2\, FSE[u]^2) / (x + u)^2) + FSE[EF]^2\}^{0.5} \quad (5)$$

Inserting a value of 0.15 for r_n and the 5 FSE values from Table 15 into equations (4), we calculate FSE[x] would be 0.075. Inserting FSE[x] of 0.075, x of 1590, u of 280 and FSE[EF] of 0.32 into equation (5), we calculate $FSE[E_{N2O}]$ would be 0.326, the Fractional Standard Error of E_{N2O}. As stated, including the indirect N_2O emissions, total E_{N2O} was 32.0 Gg, so $FSE[E_{N2O}]$ would be 10.4 Gg (= 32.0*0.326). For 95 % confidence, we require ± twice $FSE[E_{N2O}]$ or 20.4 Gg. Thus, we can be 95% certain that the true value of E_{N2O} was 32.0 ± 20.8 Gg or between 11.2 and 52.8 Gg, a (95% confidence) range of 41.6 Gg.

An assumption of independence has been made for the terms in equations (3) - (5) in order to estimate $FSE[E_{N2O}]$. If the terms had been correlated, the estimate of $FSE[E_{N2O}]$ could have been different, depending on the degree of correlation. To introduce the effects of this assumption, we will construct and analyse another, simpler representation of the inventory. This will involve subsuming
$\{[a_n\, d\, (1/e)\, p_n\, (1 – r_n)] + u\}$ into a single term called M (for "mash" factor), so equation (1) can be re-written as the product of M and EF

$$E_{N2O} = M\, EF \quad (6)$$

Assuming independence of the terms in equation (6), we would again follow a root-mean-square approach and write the following approximation

$$FSE[E_{N2O}] \approx (FSE[M]^2 + FSE[EF]^2)^{0.5} \quad (7)$$

This approximation follows from an exact expression for the product of independent terms which is given by

$$FSE[E_{N2O}] = (FSE[M]^2 + FSE[EF]^2 + FSE[M]^2\, FSE[EF]^2)^{0.5} \quad (8)$$

When FSE[M] and/or FSE[EF] are small, $FSE[M]^2\, FSE[EF]^2$ will be very small and can be ignored. Based on equation (8), $FSE[M] = ((x^2\, FSE[x]^2 + u^2\, FSE[u]^2) / (x + u)^2)^{0.5} = 0.063$ and FSE[EF] = 0.32, so $FSE[M]^{2}\, FSE[EF]^{2} = 0.0004$. Ignoring this small quantity, the approximation given by equation (7) is shown to be adequate, yielding $FSE[E_{N2O}] = 0.326$, the same estimate calculated by equation (8). However, if M and EF had been correlated, another (exact) expression would be needed. The seminal study of Goodman (1960) provides such an expression that will be the basis for our next analysis.

An exact expression for the variance (denoted var) of a product was developed by Goodman (1960) and we write

$$var[M.EF] = var[M]var[EF] + (\mu_M)^2 var[EF] + (\mu_{EF})^2 var[M] + cov[M^2,EF^2] - (cov[M,EF])^2 - 2\mu_M\mu_{EF}cov[M,EF] \quad (9)$$

where μ_M is the mean of M, μ_{EF} is the mean of EF and the cov[M,EF] is the covariance of M and EF.

Given $cov[M^2,EF^2]$ is $4\mu_M\mu_{EF}cov[M,EF]$ to order 1/n, equation (9) may be approximated by

$$\mathrm{var}[M.EF] \approx \mathrm{var}[M]\mathrm{var}[EF] + (\mu_M)^2\mathrm{var}[EF] + (\mu_{EF})^2\mathrm{var}[M] - (\mathrm{cov}[M,EF])^2 + 2\mu_M\mu_{EF}\mathrm{cov}[M,EF] \quad (10)$$

The approximation includes two terms involving the covariance of M and EF. One is subtracted and the other depends on the sign of the covariance (when the means are positive). To proceed, we briefly re-consider the situation when M and EF are independent, such that equations (9) and (10) can be reduced to the first three terms as

$$\mathrm{var}[M.EF] = \mathrm{var}[M]\mathrm{var}[EF] + (\mu_M)^2\mathrm{var}[EF] + (\mu_{EF})^2\mathrm{var}[M] \quad (11)$$

Equation (11) can be rearranged using an expression for $FSE[M] = SE[M]/\mu_M$ and $SE[M] = (\mathrm{var}[M])^{0.5}$ and $\mu_{M.EF} = \mu_M\mu_{EF}$ (because of independence) to give a Fractional Standard Error of the product M.EF as

$$FSE[M.EF] = SE[M.EF]/\mu_{M.EF} = SE[M.EF]/\mu_M\mu_{EF}$$

which can be expanded, as before for equation (8), and repeated here in a different order as

$$FSE[M.EF] = (FSE[M]^2FSE[EF]^2 + FSE[EF]^2 + FSE[M]^2)^{0.5} \quad (12)$$

Now, when M and EF are not independent, the covariance of M and EF can be expressed in terms of the correlation of M and EF, $\rho_{M,EF}$, which can be written as $\mathrm{cov}[M,EF] = \rho_{M,EF}SE[M]SE[EF]$. We can use this expression to re-write equation (10) as

$$\mathrm{var}[M.EF] \approx \mathrm{var}[M]\mathrm{var}[EF] + (\mu_M)^2\mathrm{var}[EF] + (\mu_{EF})^2\mathrm{var}[M] - (\rho_{M,EF}SE[M]SE[EF])^2 + 2\mu_M\mu_{EF}\rho_{M,EF}SE[M]SE[EF] \quad (13)$$

From equation (13), when M and EF are positively correlated with positive means, var[M.EF] will be greater than that given by equation (11) for independent M and EF when $2\mu_M\mu_{EF}/(SE[M]SE[EF]) > \rho_{M,EF} > 0$. Rearranging left inequality gives $2 > \rho_{M,EF}\,FSE[M]FSE[EF]$, which will certainly be satisfied when FSE[M] and FSE[EF] are less than 1. When M and EF are negatively correlated (with positive means), var[M.EF] will be less than that in equation (11) because the last 2 terms in equation (13) will be negative. Further, when M and EF are correlated

$$\mu_{M.EF} = \mu_M\mu_{EF} + \mathrm{cov}[M,EF] = \mu_M\mu_{EF} + \rho_{M,EF}SE[M]SE[EF]. \quad (14)$$

and

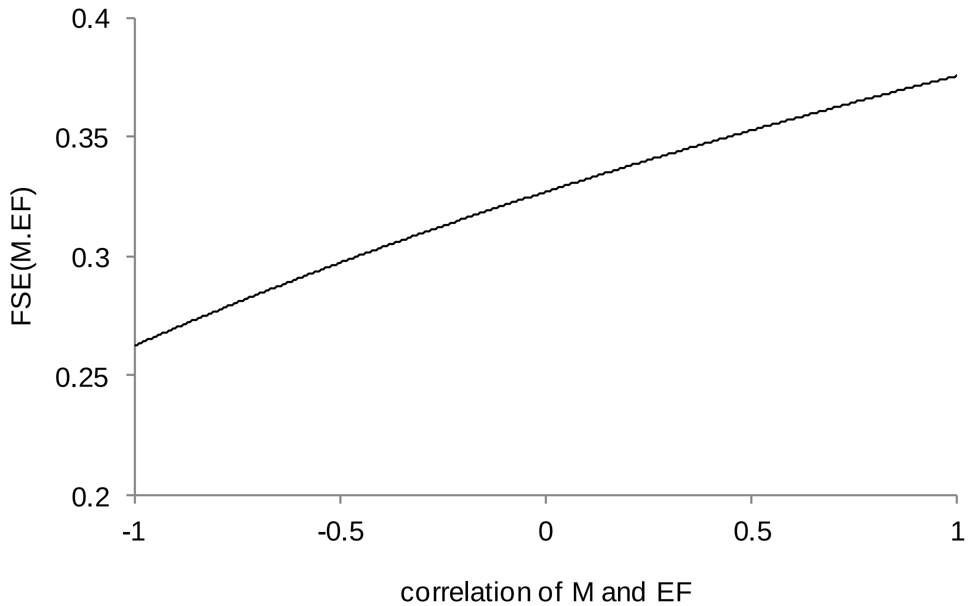
$$\mu_{M.EF}/\mu_M\mu_{EF} = (\mu_M\mu_{EF} + \mathrm{cov}[M,EF])/\mu_M\mu_{EF} = 1 + \rho_{M,EF}SE[M]SE[EF]/(\mu_M\mu_{EF}) = 1 + \rho_{M,EF}FSE[M]FSE[EF] \quad (15)$$

We can use equations (13) and (15) to derive a general expression for FSE[M.EF]. This will recognize that $FSE[M.EF] = SE[M.EF]/\mu_{M.EF}$. Moreover, from equation (15) when M and EF are correlated, we know $FSE[M.EF] = (SE[M.EF]/(\mu_M\mu_{EF}))(\mu_M\mu_{EF}/\mu_{M.EF})$. Thus, for all levels of correlation between M and EF including negative, positive and nil (independence), we can now write

$$FSE[M.EF] \approx \frac{\{FSE[M]^2FSE[EF]^2 + FSE[EF]^2 + FSE[M]^2 - (\rho_{M,EF}FSE[M]FSE[EF])^2 + 2\rho_{M,EF}FSE[M]FSE[EF]\}^{0.5}}{(1 + \rho_{M,EF}FSE[M]FSE[EF])} \quad (16)$$

To use equation (16) to determine FSE[M.EF], we require estimates of FSE[M], FSE[EF] and $\rho_{M,EF}$. We have shown that FSE[M] = 0.063 and FSE[EF] = 0.32. The estimation of $\rho_{M,EF}$ will be difficult as discussed earlier with respect to the data analyses associated with Figure 5. Alternatively, as a sensitivity analysis, we will calculate FSE[M.EF] according to a range of values of $\rho_{M,EF}$. These values can then be compared to the FSE[M.EF] estimate of 0.326 obtained earlier, assuming $\rho_{M,EF}$ was 0 (independence of M and EF). Thus, if FSE[M] and FSE[EF] were 0.063 and 0.32, respectively, and $\rho_{M,EF}$ was +0.25, +0.50, +0.75 and +1.00, FSE[M.EF] would be 0.340, 0.352, 0.364 and 0.375, respectively (Figure 9). To re-iterate, FSE[M.EF] by equation (16) depends on the value of $\rho_{M,EF}$ and for unity, FSE[M.EF] was 0.375. Thus, this maximum value for $\rho_{M,EF}$ = 1 was only 15% larger than FSE[E_{N2O}] for $\rho_{M,EF}$ = 0 that can also be calculated by equation (5) or (7). While M and EF are unlikely to be negatively correlated, we can set $\rho_{M,EF}$ to -1.0 which yields a value of 0.260, 81% of the value calculated earlier for $\rho_{M,EF}$ = 0. If FSE[M] and FSE[EF] continued to have the same values and $\rho_{M,EF}$ was -0.75, -0.50 and -0.25, FSE[M.EF] by equation (16) would be 0.280, 0.297 and 0.312, respectively (Figure 9).

Figure 9 Relation between correlation of the mash and emission factors, M and EF, and fractional standard errors (FSE) of the product. The values of M and EF and FSE[M] and FSE[EF] were 1,590 and 0.0075 and 0.063 and 0.32, respectively.



Finally, we will assess NZ's inventory of N_2O emissions (E_{N2O}) by Monte Carlo numerical simulation. This began with equation (1) including values for [a_n d (1/e) p_n (1 – r_n)] of 1590 Gg N, u of 280 Gg N, a weighted mean fractional EF of 0.008 and, as before, multiplication by 1.57 to obtain 23.5 Gg as an estimate of the direct N_2O emissions from agricultural soils during 2009. The total N_2O emissions were calculated to be 32.0 Gg by multiplying the estimate of 23.5 Gg by 1.36. For the simulations, a symmetrical, bell-shaped (normal) curve was used to represent the frequency distribution of variables, except for EF that was represented by a log normal frequency distribution. Assuming the independence of variables, a simulation indicated 95% certainty that a true value of E_{N2O} was between 16.3 and 57.8 Gg, a (95% confidence) range of 41.5 Gg. The corresponding mean and median E_{N2O} values and FSE[E_{N2O}] were 32.0 and 30.7 Gg and 0.332, respectively. This should be considered a lower limit because, according to simulations, FSE[E_{N2O}] would be 0.378, 0.398 and 0.414 (14, 20 and 25% larger, respectively) if the variables had been positively correlated with correlation coefficients of +0.50, +0.75 and +1.00, respectively. An additional set of simulations done with a symmetrical, bell-shaped curve representing the frequency distribution of all variables, including EF, indicated the corresponding values were 0.326, 0.353, 0.365 and 0.376 and to re-iterate, according to equation (16), the corresponding values were 0.326, 0.353, 0.364 and 0.375. The consistency of these three sets of calculations gave us confidence in our assessment of the inventory's uncertainty. For completeness, but unlikely in the case of E_{N2O}, by Monte Carlo numerical simulation, FSE[E_{N2O}] would be 0.287 and 0.239 smaller if the variables had been negatively correlated with correlation coefficients of -0.5 and -1.0, respectively. According to the additional set of simulations done with a symmetrical, bell-shaped curve representing the frequency distribution of all variables the corresponding values had been 0.297 and 0.264 and from equation (16) they were 0.297 and 0.262.

Earlier, Monte Carlo numerical simulation had been used to analyse inventory data for the year 1990, assuming independence of the variables, as reported by Kelliher et al. (2004). To reproduce their calculations according to equation (1), values for [a_n d (1/e) p_n (1 – r_n)] and u will be 1522 and 61 Gg N according to inventory data for the year 1990. The sum of these 2 values is 1583 Gg N, and if multiplied by an EF of 0.008 and by 1.57, an estimate of the direct N_2O emissions from agricultural soils during 1990 would be 19.9 Gg N_2O. Multiplying this value by 1.36 yields 27.1 Gg N_2O, an estimate of the total N_2O emissions from agricultural soils during 1990. A current estimate of the total N_2O emissions from agricultural soils during 1990 is 25.0 Gg N2O or 9% less. For the simulations reported by Kelliher et al. (2004), a symmetrical, bell-shaped curve was used to represent the frequency distribution of most variables. However, the variables EF1, EF3, EF4 and EF5 were represented by log normal frequency distributions. These distributions were determined in 2003 based on the available data from field trials. As has been shown by Table 10, there was less data available in 2003 to define the statistics of these EF frequency distributions. A simulation for the 1990 inventory was reported to have indicated 95% certainty that a true value of E_{N2O} was between 17.2 and 58.2 Gg, a (95% confidence) range of 39.0 Gg. The reported median was 30.7 Gg and the unreported mean had been 32.6 Gg. Thus, median and mean values from the year 1990 simulation were 13 and 20% greater, respectively, than 27.1 Gg for E_{N2O} during the year 1990 calculated according to equation (1). However, by dividing the simulated 95% confidence range for the year 1990 by 4 to estimate SE as 9.8 Gg (= 39.0/4), FSE[E_{N2O}] would be 0.301 (= 9.8/32.6) for the year 1990. This estimate of FSE[E_{N2O}] for the year 1990 inventory was only 9% less than 0.332, FSE[E_{N2O}] for the year 2009 inventory, from the Monte Carlo numerical simulation when the variables had been assumed to be independent.

6. Recommendations

• **The Olsen P level in topsoil should be measured in field trial plots.** For a subset of EF3 replicate-level data for dairy cattle and sheep urine applied to lower slope positions at 4 hill country sites in 3 regions, topsoil fertility data (Olsen P) were available for analysis. A curvilinear relation, accounting for 67% of the variability in dairy cattle and sheep urine EF3 (n = 38), and suggested that EF3 and the Olsen P level increased together. This relationship looks promising and warrants further research. Unfortunately, the Olsen P level in soils has not been measured in other field trials, so further data analyses were not possible. Further research is also warranted to examine the effects of other indicators of soil fertility (e.g. available N) on EF3 and EF1.

• **A value of 1% should be used in NZ's inventory of agricultural soil N_2O emissions for the EF3 of dairy cattle, beef cattle and sheep urine** on the basis of meta-analysis of data from 75 field measurement trials which yielded mean values of EF3 for dairy cattle and sheep urine which were not significantly different from each other or from 1%.

• **A value of 0.25% should be used for the EF3 of dairy cattle, beef cattle and sheep dung.** This value was recommended earlier by Luo et al. (2010). The results of meta-analysis of data from 36 field measurement trials yielded a mean EF3 of 0.3% for the dung of dairy cattle, beef cattle and sheep and no significant differences amongst animal types. This mean EF of 0.3% was not significantly different to the value of 0.25% reported by Luo et al. (2010). However, based on the meta-analysis, this mean EF of 0.3% was significantly less than the mean EF3 for dairy cattle and sheep urine.

• **A value of 0.7% could be used for EF1 on the basis of meta-analysis of data from 19 field measurement trials. This mean was significantly less than those of EF3 for dairy cattle and sheep urine.** Calculations using activity data for the year 2009 indicated reducing EF1 form the current value of 1% to 0.7%, and no other changes, would reduce NZ's inventory of agricultural soil N_2O emissions from 9,918 Gg CO_2-eq to 9,427 Gg CO_2-eq, a reduction of 427 Gg CO_2-eq which should have an annual monetary value of NZ$12.3 M if one tonne of CO_2-eq is worth NZ$25.

• **We think further EF1 measurement trials will be needed to support acceptance of our previous recommendation by the international community. Such trials should include more soils, regions, sites including hill country, and for completeness, urea and compound fertilisers such as DAP as well as mitigation products.** Statistical analyses have shown the subset of EF1 data analysed here is variable with a mean of 0.7 ± 0.4% for 95% confidence. The soil, region and site representation of trials which have been conducted is unbalanced as 13 of the 19 field measurement trials were conducted at Ruakura with 10 of these trials on a poorly-drained soil, Te Kowhai silt loam, and 3 on a freely-drained soil, Horotiu silt loam.

• **Mean values of EF1 and separate EF3 means for urine and dung should be used in should be used in NZ's inventory of agricultural soil N_2O emissions on the basis of meta-analysis of data from 164 field measurement trials which indicated EF3 and EF1 had been significantly affected by the form of nitrogen applied to soils (urea fertiliser, urine and dung). Further disaggregation of EF3 and EF1 based on topographic type (lowland versus hill country), soil drainage class (freely versus poorly drained), rainfall and season was not warranted. This means knowledge of these factors did not significantly affect description of the EF3 and EF1 data by the meta-analysis.** For dairy cattle and sheep urine, dairy and beef cattle and sheep dung and urea fertiliser, there have been 132 EF3 and EF1 field measurement trials including 25, 40, 60 and 3 which began in autumn, winter, spring and summer, respectively. For meta-analysis, the paucity of data for summer probably contributed to the lack of a significant seasonal effect. To our knowledge, there have been no EF3 field measurement trials during summer on seasonally-irrigated soils. **The EF3 and EF1 data analysed for this report came from field trials where direct N_2O emissions were measured after a known quantity of N was applied to soils. Thus, these trials have not included other effects of grazing animals such as compaction of soils. In future, we think field trials should examine the effects of compaction on EF3 and EF1.**

• **According to analytical and Monte Carlo numerical simulation methods, assuming independence of the variables, NZ's inventory of agricultural soil N_2O emissions for the year 2009 should be reported as 32.0 ± 21.0 Gg for 95% confidence.** This should be considered a lower limit for 95% confidence because the uncertainty level could be up to 15% larger if the variables had been positively and perfectly correlated (correlation coefficient = +1). For soil N_2O emissions, quantifying this correlation will be difficult and the available experimental data were considered equivocal. The inventory's uncertainty, and dependence on variable correlation is largely determined by the emission factor standard error, estimated by meta-analysis of field trial data to be 32% of the mean. Activity data determine the corresponding nitrogen application rate onto agricultural soils and the estimated standard error for this component of the inventory was 6% of the mean.

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9. Appendix

Appendix. Dairy urine cattle: 24 trials when measured rain was less than typical including 15 trials when the difference was statistically significant.

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF3 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p<0.05)
Trial rain less than normal:											
Invermay	Freely	548	22-Oct-2008	7-Apr-2009	167	0.42	39	November	66	-27	*
Invermay	Poorly	548	22-Oct-2008	7-Apr-2009	167	0.21	39	November	66	-27	*
Lincoln	Imperfect	1000	6-May-2008	3-Sept-2008	120	0.42	11	May	64	-53	*
Lincoln	Imperfect	1000	3-Sep-2008	4-Nov-2008	62	0.10	44	September	47	-3	
Lincoln	Freely	1000	20-May-2009	24-Nov-2009	188	1.67	30	June	63	-33	*
Lincoln	Imperfect	700	28-May-2009	18-Nov-2009	179	0.77	20	June	63	-43	
Massey	Poorly	700	28-May-2009	31-Oct-2009	156	0.80	34	June	85	-51	*
Massey	Poorly	600	4-Jun-2009	15-Oct-2009	133	3.61	84	June	85	-1	
Massey	Poorly	700	30-Apr-2010	8-Nov-2010	192	0.41	59	May	93	-34	*
Ruakura	Freely	436	20-Feb-2002	15-Nov-2002	268	0.13	64	March	79	-14.9	
Ruakura	Poorly	436	20-Feb-2002	15-Nov-2002	268	0.62	64	March	79	-14.9	
Ruakura	Freely	581	18-Oct-2002	12-Aug-2003	298	1.28	50	November	96	-45.8	*
Ruakura	Poorly	581	18-Oct-2011	12-Aug-2003	298	2.81	50	November	96	-45.8	*
Ruakura	Poorly	1000	7-Apr-2004	7-May-2004	30	0.05	80	April	98	-18	
Ruakura	Poorly	1000	30-Jun-2004	19-Aug-2004	50	1.59	89	July	125	-36	
Ruakura	Poorly	1000	19-Feb-2005	10-Mar-2005	19	0.02	14	March	79	-65	*
Ruakura	Freely	496	20-May-2008	22-Sep-2008	125	0.10	66	June	126	-60	*
Ruakura	Poorly	496	20-May-2008	22-Sep-2008	125	0.51	66	June	126	-60	*
Ruakura	Freely	551	22-Oct-2008	7-Apr-2009	167	0.41	80	November	96	-16	
Ruakura	Poorly	551	22-Oct-2008	7-Apr-2009	167	0.91	80	November	96	-16	

Ruakura	Freely	995	22-May-2009	12-Dec-2009	204	0.48	72	June	126	-54	*
Telford	Imperfect	547	22-May-2009	17-Dec-2009	209	1.15	34	June	126	-92	*
Tokanui	Freely	691	29-May-2009	30-Dec-2009	215	0.13	72	June	126	-54	*
Tokanui	Freely	713	22-Apr-2010	18-Aug-2010	118	0.32	62	May	114	-52	*

Appendix. Dairy cattle urine: 22 trials when measured rain was more than typical, including 1 trial when the difference was statistically significant.

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF3 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p>0.95)
Trial rain more than normal:											
Invermay	Freely	499	20-May-2008	29-Sep-2008	132	0.93	82	June	61	21	
Invermay	Poorly	499	20-May-2008	29-Sep-2008	132	0.53	82	June	61	21	
Lincoln	Freely	1000	14-May-2008	10-Oct-2008	149	3.03	70	May	64	6	
Lincoln	Freely	1000	14-May-2008	10-Oct-2008	149	2.02	70	May	64	6	
Lincoln	Imperfect	1000	14-May-2008	10-Oct-2008	149	1.87	70	May	64	6	
Lincoln	Freely	1000	14-May-2008	10-Oct-2008	149	3.85	130	May	64	66	
Lincoln	Freely	1000	14-May-2008	10-Oct-2008	149	1.52	130	May	64	66	
Lincoln	Imperfect	1000	14-May-2008	10-Oct-2008	149	1.36	130	May	64	66	
Lincoln	Imperfect	1000	12-May-2009	19-Oct-2009	160	1.38	87	May	64	23	
Lincoln	Freely	1000	21-May-2009	21-Nov-2009	184	1.67	76	June	63	13	
Lincoln	Imperfect	700	29-Apr-2010	24-Sep-2010	148	1.94	155	May	64	91	*
Massey	Poorly	600	4-Jun-2009	4-Nov-2009	153	1.54	110	June	85	25	
Newstead	Freely	592	11-May-2000	30-Jun-2000	50	0.37	116	May	114	2.2	

Ruakura	Freely	592	11-May-2000	22-Sep-2000	134	0.70	116	May	114	2.2
Ruakura	Poorly	1000	20-Aug-2003	6-Oct-2003	47	0.67	140	September	99	41
Ruakura	Freely	500	25-Aug-2003	25-Mar-2004	213	0.90	133	September	99	34
Ruakura	Poorly	500	25-Aug-2003	25-Mar-2004	213	3.22	133	September	99	34
Ruakura	Poorly	1000	12-Nov-2003	16-Dec-2003	34	0.71	150	November	96	54
Ruakura	Poorly	1000	23-Nov-2004	2-Jan-2005	40	0.17	95	December	88	7
Ruakura	Poorly	1000	7-Jul-2005	18-Aug-2005	42	0.72	167	July	125	42
Telford	Imperfect	700	18-May-2010	22-Nov-2010	188	3.21	109	June	61	48
Tussock Cr.	Poorly	673	12-May-2009	16-Nov-2009	188	1.36	119	May	99	20

Appendix. Urea fertiliser: 8 trials when measured rain was less than typical, including 4 trials when the difference was statistically significant, and 9 trials when measured rain was more than typical.

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF1 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p<0.05 or p>0.95)
Trial rain less than normal:											
Invermay	Freely	50	1-Oct-2010	16-Nov-2011	46	0.05	26	October	53	-27	*
Lincoln	Freely	200	20-May-2009	24-Nov-2009	188	0.14	30	June	63	-33	*
Massey	Poorly	50	4-Jun-2009	15-Oct-2009	133	2.57	84	June	85	-1	
Ruakura	Poorly	50	7-Apr-2004	7-May-2004	30	0.03	80	April	98	-18	
Ruakura	Poorly	50	30-Jun-2004	19-Aug-2004	50	2.63	89	July	125	-36	
Ruakura	Poorly	50	19-Feb-2005	21-Mar-2005	30	-0.01	14	March	79	-65	*
Ruakura	Freely	150	22-May-2009	22-Dec-2009	214	0.23	72	June	126	-54	
Ruakura	Freely	50	22-Oct-2010	2-Dec-2010	41	0.02	16	November	96	-80	*
Trial rain more than normal:											
Invermay	Freely	50	21-Jan-2011	22-Mar-2011	60	0.00	108	February	52	56	
Lincoln	Freely	100	21-May-2009	21-Nov-2009	184	0.29	76	June	63	13	
Massey	Poorly	50	4-Jun-2009	4-Nov-2009	153	1.66	110	June	85	25	
Ruakura	Poorly	50	9-Jun-2003	9-Jul-2003	30	0.46	148	June	126	22	
Ruakura	Poorly	50	20-Aug-2003	6-Oct-2003	47	1.21	140	September	99	41	
Ruakura	Poorly	50	12-Nov-2003	16-Dec-2003	34	0.49	150	November	96	54	
Ruakura	Poorly	50	23-Nov-2004	2-Jan-2005	40	0.11	95	December	88	7	
Ruakura	Poorly	50	7-Jul-2005	18-Aug-2005	42	0.61	167	July	125	42	
Ruakura	Poorly	50	7-Feb-2011	26-Apr-2011	68	0.30	89	February	81	9	

Appendix. Rainfall- Beef dung

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF3 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p<0.05 or p>0.95)
Trial rain less than normal:											
Ballantrae	Freely	654	20-May-2008	29-Sep-2008	132	0.06	57	June	102	-45	*
Ballantrae	Poorly	654	20-May-2008	29-Sep-2008	132	0.01	57	June	102	-45	*
Trial rain more than normal:											
Ballantrae	Freely	671	22-Oct-2008	6-Apr-2009	166	0.00	167	November	91	76	
Ballantrae	Poorly	671	22-Oct-2008	30-Mar-2009	159	0.00	167	November	91	76	

Appendix. Rainfall- Dairy cow dung

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF3 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p<0.05 or p>0.95)
Trial rain less than normal:											
Invermay	Freely	1084	22-Oct-2008	14-Apr-2009	174	0.04	39	November	66	-27	*
Invermay	Poorly	1084	22-Oct-2008	14-Apr-2009	174	0.01	39	November	66	-27	*
Lincoln	Freely	1000	28-May-2009	18-Nov-2009	174	0.17	20	June	63	-43	*
Massey	Poorly	1000	28-May-2009	31-Oct-2009	156	0.02	34	June	85	-51	*
Ruakura	Freely	1039	20-May-2008	22-Sep-2008	125	0.03	66	June	126	-60	*
Ruakura	Poorly	1039	20-May-2008	22-Sep-2008	125	0.07	66	June	126	-60	*
Ruakura	Freely	900	22-Oct-2008	7-Apr-2009	167	0.16	80	November	96	-16	
Ruakura	Poorly	900	22-Oct-2008	7-Apr-2009	167	0.10	80	November	96	-16	
Tokanui	Well	1124	29-May-2009	30-Dec-2009	215	0.06	72	June	128	-56	*
Trial rain more than normal:											
Invermay	Freely	1169	20-May-2008	29-Sep-2008	132	0.19	82	June	61	21	
Invermay	Poorly	1169	20-May-2008	29-Sep-2008	132	0.00	82	June	61	21	
Invermay	Freely	977	22-Aug-2003	16-Mar-2004	207	0.35	---	September	44	---	
Invermay	Poorly	977	22-Aug-2003	16-Mar-2004	207	0.05	---	September	44	---	
Lincoln	Imperfect	1100	16-Oct-2002	11-Sep-2003	330	0.24	---	November	52	---	
Lincoln	Imperfect	1390	20-Feb-2002	8-Nov-2002	261	0.34	---	March	57	---	
Ruakura	Freely	1174	18-Oct-2002	12-Aug-2003	298	0.21	---	November	96	---	

Ruakura	Poorly	1174	18-Oct-2002	12-Aug-2003	298	0.64	---	November	96	---
Telford	Imperfect	1001	22-May-2009	17-Dec-2009	209	0.17	---	June	70	---

Appendix. Rainfall- Sheep urine

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF3 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p<0.05 or p>0.95)
Trial rain less than normal:											
Invermay	Poorly	237	18-Oct-2005	29-Nov-2005	42	0.21	30	November	66	-36	*
Invermay	Poorly	237	13-Oct-2006	16-Nov-2006	34	0.10	41	October	53	-12	
Ballantrae	Poorly	237	20-Oct-2006	21-Nov-2006	32	0.14	71	November	91	-20	
Trial rain more than normal:											
Invermay	Freely	47	22-Aug-2003	16-Mar-2004	207	1.23	---	September	44	---	
Invermay	Poorly	47	22-Aug-2003	16-Mar-2004	207	0.33	---	September	44	---	
Invermay	Poorly	219	16-Oct-2002	29-Jul-2003	286	0.09	---	November	66	---	
Invermay	Freely	219	16-Oct-2002	29-Jul-2003	286	0.23	---	November	66	---	
Hindon	Freely	224	26-Sep-2009	16-Dec-2009	81	0.32	55	October	55	0	
Hindon	Freely	149	26-Sep-2009	16-Dec-2009	81	0.04	58	October	55	3	
Woodville	Well	464	21-Sep-2009	26-Jan-2010	127	1.37	188	October	85	103	*
Woodville	Well	309	21-Sep-2009	26-Jan-2010	127	0.21	188	October	85	103	*
Ballantrae	Poorly	237	19-Oct-2005	29-Nov-2005	41	0.10	344	November	91	253	*
Ballantrae	Poorly	504	22-Sep-2009	15-Dec-2009	84	0.07	257	October	113	144	*
Ballantrae	Poorly	336	22-Sep-2009	15-Dec-2009	84	0.00	257	October	113	144	*
Whatawhata	Freely	263	23-Sep-2009	15-Feb-2010	145	0.99	293	October	137	156	*
Whatawhata	Freely	171	23-Sep-2009	20-Dec-2009	88	0.06	293	October	137	156	*

Appendix. Rainfall- Sheep dung

Site	Soil drainage class	N rate (kg N ha^{-1})	Trial start date	Trial end date	Trial duration (days)	EF3 Arithmetic mean	Cumulative rainfall– first 30 days of trial (mm)	Month representing first 30 days of trial	Long term mean monthly rain (mm)	Trial rain minus mean rain (mm)	Significant difference (p<0.05 or p>0.95)
Trial rain less than normal:											
Invermay	Freely	273	22-Oct-2008	14-Apr-2009	174	0.12	39	November	66	-27	*
Invermay	Poorly	273	22-Oct-2008	14-Apr-2009	174	-0.07	39	November	66	-27	*
Ruakura	Freely	449	20-May-2008	22-Sep-2008	125	0.03	66	June	126	-60	*
Ruakura	Poorly	449	20-May-2008	22-Sep-2008	125	0.04	66	June	126	-60	*
Ruakura	Freely	317	22-Oct-2008	7-Apr-2009	167	0.06	80	November	96	-16	
Ruakura	Poorly	317	22-Oct-2008	7-Apr-2009	167	-0.19	80	November	96	-16	
Ballantrae	Freely	273	20-May-2008	29-Sep-2008	132	-0.01	57	June	102	-45	*
Ballantrae	Poorly	273	20-May-2008	29-Sep-2008	132	0.01	57	June	102	-45	*
Trial rain more than normal:											
Invermay	Freely	351	20-May-2008	29-Sep-2008	132	0.11	82	June	61	21	
Invermay	Poorly	351	20-May-2008	29-Sep-2008	132	0.03	82	June	61	21	
Invermay	Freely	355	16-Oct-2002	29-Jul-2003	286	0.00	---	November	66	---	
Invermay	Poorly	357	16-Oct-2002	29-Jul-2003	286	-0.01	---	November	66	---	
Ballantrae	Freely	290	22-Oct-2008	6-Apr-2009	166	0.02	167	November	91	76	
Ballantrae	Poorly	290	22-Oct-2008	30-Mar-2009	159	0.00	167	November	91	76	