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Statistical analysis of nitrous oxide emission factors from pastoral agriculture field trials conducted in New Zealand☆

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ABSTRACT

Between 11 May 2000 and 31 January 2013, 185 field trials were conducted across New Zealand to measure the direct nitrous oxide (N_2O) emission factors (EF) from nitrogen (N) sources applied to pastoral soils. The log(EF) data were analysed statistically using a restricted maximum likelihood (REML) method. To estimate mean EF values for each N source, best linear unbiased predictors (BLUPs) were calculated. For lowland soils, mean EFs for dairy cattle urine and dung, sheep urine and dung and urea fertiliser were 1.16 ± 0.19% and 0.23 ± 0.05%, 0.55 ± 0.19% and 0.08 ± 0.02% and 0.48 ± 0.13%, respectively, each significantly different from one another ($p < 0.05$), except for sheep urine and urea fertiliser. For soils in terrain with slopes >12°, mean EFs were significantly lower. Thus, urine and dung EFs should be disaggregated for sheep and cattle as well as accounting for terrain.
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1. Introduction

Across one-quarter of the global land surface area, the single, most extensive activity is managed grazing of animals for the production of meat, milk and fibre (Asner et al., 2004). Worldwide, agricultural soils produce over 40% of emissions of the third most important greenhouse gas, nitrous oxide (N_2O) according to Denman et al. (2007). In the atmosphere, the lifetime of N_2O is 100–150 years and it is the single most important precursor to compounds that deplete stratospheric ozone, adding to its significance as an environmental pollutant (Ravishankara et al., 2009). The strength of agricultural soil emissions as an N_2O source can be estimated by compiling an inventory, as done annually by signatory nations in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). Grassland occupies 41% of New Zealand's (NZ's) land area and pastoral agriculture is the country's main economic activity. In accordance with NZ's commitment to the UNFCCC, a pastoral agriculture soils inventory of N_2O emissions is compiled and reported annually. Between 1990 and 2011, the most recently reported year of data, NZ's inventory increased by 29% from 25.4 to 32.8 Gg N_2O y^{-1} (Ministry for the Environment, 2013). For UNFCCC inventories, a primary variable is the direct emission factor (EF), the proportion of the quantity of nitrogen (N) applied to soils emitted into the atmosphere as N_2O.

For NZ's inventory, the primary N sources are excreta from farmed, grazing animals (1449 and 1523 Gg N y^{-1} for 1990 and 2011, respectively, estimated from animal production data described by Kelliher et al. (2007)) and N fertiliser (59 and 360 Gg N y^{-1} for 1990 and 2011, respectively, from N fertiliser sales records). Currently, NZ's inventory includes a 'country-specific' EF of 1% for sheep and cattle urine and N fertiliser and 0.25% for sheep and cattle dung.

For NZ's inventory, the excreta EFs have been determined from a subset of results from the field trial data to be analysed here (e.g., de Klein et al., 2003; van der Weerden et al., 2011). Alternatively, the N fertiliser EF follows a recommendation of the Intergovernmental Panel on Climate Change (IPCC, Mosier et al., 1998; Bouwmann

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et al., 2002). During NZ's field trials, direct N_2O emissions were measured after a known quantity of N was applied to plots of soil beneath pasture, earlier grazed by farmed sheep and cattle (e.g., Luo et al., 2007, 2008). Emissions measurements were made regularly in these plots by the static chamber method (de Klein et al., in press), and in nearby control plots that had not received an N application, until emissions from the treated plots were not (statistically) significantly different from the controls ($p < 0.05$). During the trials, animals were excluded, precluding other effects of grazing such as compaction. Seven sources of N that have been applied to soils will be the basis for data analysis, including dairy cattle urine and dung, beef cattle urine and dung, sheep urine and dung and urea fertiliser.

For this paper, we analysed the results of NZ's 185 field trials conducted between 11 May 2000 and 31 January 2013 and report a quantitative synthesis across the multiple studies by statistical analysis. We aimed to overcome some of the limitations of low statistical power for individual trials and test the 'generality' of such results (Hungate et al., 2009; van Groenigen et al., 2011). We estimated mean EFs and standard errors for each of the 7 N sources, and determined if differences are statistically significant or not. Soil and environmental variables considered to have affected the results are discussed.

2. Methods

A statistical analysis was conducted on the EF data. We used data from 125 field trials, but some involved more than one N source (type of N applied to the soil)(e.g., Luo et al., 2013), so that on the basis of individual N sources, we had 185 field trials. The trials varied in design and number of replicates. In all cases, for each trial, we calculated a mean EF value as (mean of treated reps − mean of control reps)/N applied; a second analysis was done for median EF values calculated using the median of the reps rather than means.

The field trial data were compiled at the replicate level for seven sources of N including dairy cattle urine (71 trials), dairy cattle dung (24), beef cattle urine (8), beef cattle dung (16), sheep urine (24), sheep dung (20) and urea fertiliser (22). These data included N application rates and cumulative N_2O emissions over the period when the mean of the treated replicates ($n = 4$–12) had N_2O emissions significantly greater than the mean of the controls ($n = 4$–12). On this basis, overall, 71% of 185 trials lasted longer than 120 days. In contrast, 45% of the 22 trials involving urea fertiliser lasted less than 60 days. However, there were no significant relations between trial duration and EF for any sources of N (data not shown).

Rainfall determines soil wetness and we postulated soil wetness during a field trial could affect the trials' EF (e.g., van der Weerden et al., 2012). On this basis, atypical rainfall might correspond with an atypical trial EF. 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 alone and rainfall during a trial was deemed atypical or not based on the statistical significance ($p < 0.05$) of comparisons with long-term means from the closest weather station. After N application to soils, generally, most of the (cumulative) total N_2O emissions occur within the first month. On this basis, we compiled rainfall data for the first month after N application to soils. 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 forming a ratio with a long-term monthly mean rainfall statistics based on data from the closest weather station. Most weather stations were located a few km from the trial site and the statistics were mostly calculated from 30 years of data. Otherwise, proximity to the trial site was most important and the period for the statistics as long as possible. When a trial began in the first half of a month, the rainfall ratio was based on a long-term mean for that month. Alternatively, when a trial began in the second half of a month, the rainfall ratio was based on a long-term mean comparison for the following month.

The fate of rainfall in soils depends on drainage. The field trials and sites were classified according to 2 drainage classes, freely versus poorly, on the bases of soil colour and the depth of such colour as a simplification of hydromorphic classes used in the New Zealand soil classification system (Hewitt, 2010). Briefly, for freely drained soils, the cut face of a hole dug to a depth of 0.9 m indicated <2% of the area had high chroma, red masses ≥ 6 in Munsell notation (Milne et al., 1995). For the uppermost 0.3 m depth of poorly drained soils, ≥50% of the area appeared greyish due to the low chroma. By GIS overlays, we estimated 75% of NZ's grassland area had freely drained soils. In order not to pre-suppose a relation between the rainfall ratio and EF values, 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 15th day occurred as follows: January, February and December for summer, March, April and May for autumn, June, July and August for winter and September, October and November for spring. The field trials and sites were also classified according to three topographic types; namely, lowland (dominant-land slope < 15°) versus hill country and for hill country, low and medium slope positions ("local" slope classes < 12° and 12–25°, respectively).

At lowland sites, 113 trials (61%) were conducted on 13 different soils in six, climatically-distinct regions. For 11 M ha of grassland across New Zealand, 47% was classified as lowland on the basis of dominant slope <15° according to GIS overlays. In hill country (dominant slope > 15°), 72 trials were done on six other soils in three regions, 78 and 22% on low and medium slope positions, respectively. In comparison, de Klein et al. (2009) estimated that 58% of grazing animal urine and dung was excreted onto low slope positions. Based on soil drainage class, 56% and 44% of the trial sites were freely- and poorly-drained, respectively, slightly under-representing the estimated 75% of NZ's grassland area with freely-drained soils. By season, 29% of trials began in autumn, 23% in winter, 34% in spring and 14% in summer.

Separating the effects of these factors from results of these field trials can be problematic because there are confounding effects. For instance, EF data for some N sources were only available for lowland sites and others only on hill country sites. As an example, the 20 trials that measured the EF of dairy cattle dung were conducted at lowland sites. To deal with such issues, data were analysed using a restricted maximum likelihood (REML) method with the effects modelled as random effects. In accordance with the frequency distribution, the EF values were log transformed for REML analyses (e.g., Fig. 1). The effects were trial, site, N source, topographic type, drainage class, rain ratio, season and the interaction between N source and topographic type. The BLUPs estimated for the effects were back-transformed and bias corrected. The bias correction was done by scaling the back-transformed estimates by the amount required to get their weighted mean to be the same as the overall mean of the EF value.

3. Results

Log-transformed medians and means of the reps yielded similar means and SE for the analysis, indicating the robustness of this approach (the data calculated using the medians will not be shown). There was a statistically significant (positive) effect of rainfall ratio on EF and we retained all non-zero variance components such as the soil drainage class and season. For example, while a significance level of 0.16 came from a test to determine if N source differences depended on site topography (lowland versus hill country low slope position versus hill country medium slope position), we proceeded with analysis including a site topography interaction.

For the lowland soils, means for dairy cattle urine and dung, sheep urine and dung and urea fertiliser were 1.16 and 0.23%, 0.55 and 0.08% and 0.48%, respectively, each significantly different from one another ($p < 0.05$), except for sheep urine and urea fertiliser (Table 1). For low slope positions on hill country soils, the dairy

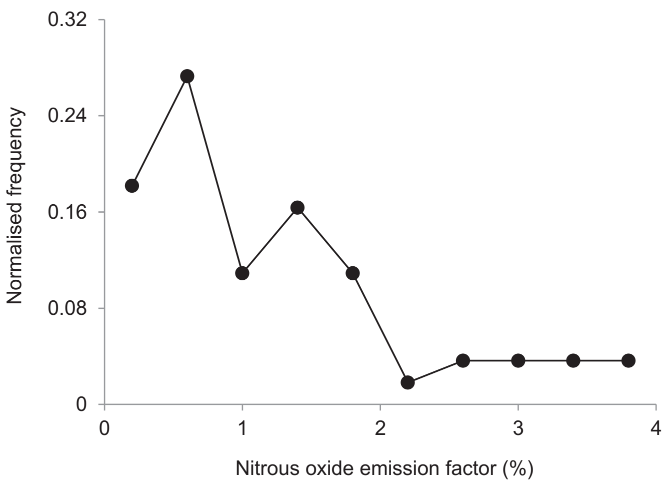

Fig. 1. Frequency distribution of nitrous oxide emissions factors for dairy cattle urine applied to lowland soils, a subset of the data with the largest number of trials ($n = 55$). The Y axis has been normalised, so the area under the curve equals unity.

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Table 1
Best linear unbiased predictors (BLUPs) for direct nitrous oxide emission factors (%, mean ± SE, n) of seven nitrogen (N) sources.

Topography	Lowland	Hill country, low slope	Hill country, medium slope
N source			
Dairy cattle urine	1.16 ± 0.20, 55	0.84 ± 0.20, 16	
Dairy cattle dung	0.23 ± 0.05, 20	0.20 ± 0.07, 4	
Beef cattle urine		0.99 ± 0.37, 4	0.32 ± 0.12, 4
Beef cattle dung		0.21 ± 0.06, 12	0.06 ± 0.02, 4
Sheep urine	0.55 ± 0.19, 4	0.40 ± 0.10, 12	0.16 ± 0.05, 8
Sheep dung	0.08 ± 0.02, 12	0.11 ± 0.03, 8	
Urea fertiliser	0.48 ± 0.13, 22		

cattle urine and dung, beef cattle urine and dung, and sheep urine and dung means were 0.84 and 0.20%, 0.99 and 0.21%, and 0.40 and 0.11%, respectively. For each animal type, the urine and dung means were significantly different. For dairy cattle urine and dung and sheep urine and dung, mean EFs for low slope positions on hill country soils were not significantly different to those on lowland soils. Moreover, for low slope positions on hill country soils, mean EFs for dairy cattle, beef cattle and sheep urine were not significantly different from one another nor were the three corresponding mean EFs for dung. For medium slope positions on hill country soils, the beef cattle urine and dung and sheep urine means were 0.32 and 0.06 and 0.16%, respectively. The beef cattle urine and dung means were significantly different, but the beef cattle and sheep urine were not, nor was sheep urine different to beef cattle dung. For beef cattle urine and dung and sheep urine on hill country soils, the mean EF values for low and medium slope positions were significantly different.

4. Discussion

For lowland soils and hill country soils, low slope position, the mean EF for dairy cattle urine (1.16 and 0.84%, respectively) was 111% greater than that for sheep urine (0.55 and 0.40%, respectively) and both differences were statistically significant. For dairy cattle urine, the mean N application rate was 719 ± 29 kg N ha^{-1} ($n = 71$), 183% greater than that of sheep urine (254 ± 29 kg N ha^{-1}, $n = 16$). On this proportional basis, the urine EF difference has not been explained by the different N application rates, a result consistent with de Klein et al. (in press). However, when urine was applied to the surface, some infiltrated, moving downwards through the soil. The deeper it infiltrates the greater the chance of interaction with N_2O-producing bacteria. For the trials, 10 L m^{-2} of dairy cattle urine was applied as a treatment and typically 4 L m^{-2} for sheep urine, so when applied to soil of a given water content and pore size distribution, the dairy cattle urine should have penetrated 150% deeper, actual depths also depending on the antecedent water content. Moreover, for the EF measurement, cow urine had been applied across the entire (soil surface) area of a chamber base (491 cm^2), while sheep urine was applied across the innermost 380 cm^2. Combining the differences of urine penetration and surface area coverage, cow urine should have been in contact with 193% greater volume of soil than sheep urine. This proportional difference is substantially greater than 111% between the cow and sheep urine EFs. Alternatively, the most deeply penetrating cow urine may not have contributed to N_2O emissions measured at the surface.

For lowland soils and hill country soils, sheep and cattle urine EF was significantly greater than the corresponding dung EF. While for lowland soils, dairy cattle dung EF was significantly greater than sheep dung EF, for the low slope position on hill country soils, the three corresponding EFs for dung were not. For an animal type, the N application rate for dung did not differ significantly between lowland soils and the low slope position of hill country soils. Moreover, the N application rate for dung did not differ significantly between the low and medium slope positions. Overall, N application rates for the dung of dairy cattle, beef cattle and sheep were 1046 ± 24 ($n = 24$), 833 ± 51 and 308 ± 15 kg N ha^{-1}, respectively, each significantly different from one another. For dairy cattle, the mean N application rate for dung was 45% greater than for urine, the corresponding percentages were 108 and 21% for beef cattle and sheep, respectively, and the mean N application rate for beef cattle urine was 400 ± 37 kg N ha^{-1}. Thus, consistently, dung had the lowest EF, evidently unaffected by a widely ranging N application rate (e.g., Luo et al., 2013). Alternatively, during the trials, dung may have dried at a relatively consistent rate, keeping in mind when dung dries, the N_2O emissions will be reduced (van der Weerden et al., 2012). Moreover, the dung surface may become hydrophobic, reducing the potential effects of subsequent rainfall and soil moisture on decomposition (Shand and Coutts, 2006). If dung EF is mostly influenced by the weather, which can also affect soil conditions, our results suggest the weather and soils were broadly 'consistent' during most of the trials. Only 27 of 185 trials began in summer, while during autumn, winter and spring, the sites were usually cool, of order 5–15 °C, and generally subjected to rainfall on a regular basis.

For lowland soils, the mean EF for dairy cattle urine was 142% greater than that for urea fertiliser and the difference was statistically significant, but the small difference between the mean EFs for urea fertiliser and sheep urine was not. For 19 of 22 urea fertiliser EF measurement trials, the N application rate was 50 kg N ha^{-1}. As stated, the mean N application rates for dairy cattle and sheep urine were 719 and 254 kg N ha^{-1}, so once again, we cannot account for proportional differences between the EFs on the basis of N application rate. While unmeasured, pasture plant uptake would have been a sink for the applied N during the trials. Pasture plant uptake should have represented a greater proportion of the applied N for urea fertiliser than for dairy cattle urine as well as sheep urine. This might have made the difference in N application rate between dairy cattle urine and urea fertiliser sufficiently large to have affected the EFs, but evidently not the EFs of urea fertiliser versus sheep urine. This possible explanation would be consistent with other results reported by de Klein et al. (in press) whereby at very low N_2O emission rates in their free draining soils there was a statistically significant trend of increasing EFs with the N application rate.

Statistical analysis has not included an assessment of measurement uncertainty associated with the mean EFs. For this purpose, trial 39 was chosen as representative. For this trial, on 30/6/04, dairy cattle urine (1000 kg N ha^{-1}) was applied to 12 replicate plots of Te Kowhai soil beneath pasture at Ruakura near Hamilton (37.8°S, 175.3°E, 40 m above sea level)(Luo et al., 2008). Afterwards, over 50 days until 19/8/04, the emissions were measured on 11 occasions. The precision of our GC system was assessed by measuring the N_2O concentration of 20 replicate samples of ambient air, and typically, the standard deviation (SD) was 1.25% of the mean. Combining this percentage, a chamber height of 16 cm and an air sampling interval of 1 h, we calculated the minimum N_2O emission rate which could be reliably measured, 1.7 μg N_2O–N m^{-2} h^{-1} including twice the SD for 95% confidence. To assess the measurement uncertainty of an EF, we assumed each emissions measurement had been independent. For each replicate, we integrated the area under the 50-d-long curve for emissions measurements. An overall SD was then calculated to represent the measurement uncertainty which was 1.43% of the mean EF, only slightly more than the GC measurement SD which governed this calculation. In contrast, a 'spatial' SD was 31% of the mean EF, calculated using EF data from the 12 replicates.

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Global mean EFs for (all) N fertiliser and urea fertiliser were 1.0 and 1.1%, respectively, based on a meta-analysis of data from 846 field trials (Bouwmann et al., 2002). The reported uncertainty range for these means was −40% and +70%, so 0.60–1.70% for N fertiliser and 0.66–1.87% for urea fertiliser. From our statistical analysis of NZ's available data, the mean EF for urea fertiliser was much smaller, 0.48 ± 0.13% (±SE), clear evidence of an EF less than 1%. A mean EF should be the best estimate, so for NZ's inventory, the EF for N fertiliser should be reduced from 1% to 0.48%.

The IPCC have recommended mean EFs of 1% for the urine and dung of sheep and 2% for the urine and dung of cattle (de Klein, 2004). Statistical analysis of NZ's available data from lowland soils and hill country soils, low slope position, indicated mean EFs for the urine and dung of sheep were 0.48% and 0.10%, respectively. Consequently, for NZ's inventory, the EF for urine and dung of sheep should be disaggregated into these two mean values. Using these two mean values, a combined EF for the urine and dung of sheep would be 0.35%, calculated by weighting the disaggregated EFs by 0.66 for urine and 0.34 for dung according to sheep N excretion calculations by NZ's inventory methodology. For hill country soils, the mean EF for sheep urine on the medium slope position was 60% less than that on the low slope position, suggesting further disaggregation on the basis of slope position would be warranted for NZ's inventory. For dairy and beef cattle, combining the available data from lowland soils and hill country soils, low slope position, mean EFs for the urine and dung were 1.00% and 0.21%, respectively. Thus, for NZ's inventory, the EF for cattle urine and dung of should be disaggregated into these two mean values. Using these two mean values and the described weighting calculations, a combined EF for the urine and dung of cattle would be 0.73%. For hill country soils, mean EFs for beef cattle urine and dung on medium slope positions averaged 70% less than those on low slope positions, further supporting a recommendation of disaggregation on the basis of slope position for NZ's inventory.

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