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Short communication

Refining the New Zealand nitrous oxide emission factor for urea fertiliser and farm dairy effluent

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ABSTRACT

Applications of urea fertiliser and farm dairy effluent (FDE) to New Zealand pastures are the second and third largest sources of nitrous oxide (N_2O) emissions, after emissions from excreta deposited during grazing (urine and dung). New Zealand currently employs emission factors (EF_1) (percentage of N applied which is emitted as N_2O) of 0.48% and 1% for urea fertiliser and FDE, respectively, for calculating its national N_2O inventory. The country specific emission factors for urine and dung are 1% and 0.25% respectively. Because FDE has a higher organic nitrogen (N) content than urea, and because it is a diluted mixture of urine and dung, the mean FDE EF_1 is expected to be less than 1%. With a recent increase in research trials measuring EF_1 for FDE and urea, the objective of this study was to refine New Zealand-specific EF_1 values for these N sources. We analysed urea fertiliser and FDE N_2O emission data from 45 EF_1 field trials conducted in New Zealand. This meta-analysis yielded a combined (urea and FDE) EF_1 mean of 0.46% (95% confidence interval of 0.07% and 0.90%), with EF_1 means for urea and FDE of 0.59% and 0.25%, respectively. There was no statistical difference between urea fertiliser and FDE EF_1 values. However, we recommend separate country-specific EF_1 means of 0.6 and 0.3% for urea fertiliser and FDE, respectively, for New Zealand's agricultural soils N_2O emissions inventory due to the different origin and characteristics of these N sources.

1. Introduction

Nitrous oxide (N_2O) is the third most important anthropogenic greenhouse gas and the largest remaining anthropogenic stratospheric ozone depleting substance currently being emitted, with agriculture as its largest source, representing 66% of total emissions (Davidson and Kanter, 2014). The rapid global increase in synthetic nitrogen (N) fertiliser use and the intensification in livestock farming, resulting in growing volumes of animal excreta and manure, are contributing to the increasing atmospheric N_2O concentrations (Davidson, 2009). It has been estimated that global fertiliser use will increase 50% from 2006 to 2050 (Sutton and Bleeker, 2013).

In New Zealand's pasture-grazed livestock systems, excreta deposited by the grazing animal (i.e. urine and dung) is the largest source of N_2O emissions. However, following global trends, the amount of synthetic N fertiliser applied to agricultural soils has increased from 59 kt in 1990 to 359 kt in 2013, with 80% of the total represented as urea fertiliser (Ministry for the Environment, 2015). In addition, recent increase in the number of dairy animals has resulted in a doubling of the amount of farm dairy effluent (FDE) applied to land, from 18 kt in 1990 to 39 kt in 2013 (Ministry for the Environment, 2015). Farm dairy effluent is a mixture of excreta and water derived from the washdown of dairy cow milking sheds and associated yards. This is the most common form of animal manure collected and applied to New Zealand pastoral soils (Laubach et al., 2015).

Direct N_2O emissions following application of synthetic N fertiliser and animal manures to agricultural soils are included in national N_2O inventories, and are calculated by multiplying the amount of N applied by the direct N_2O emission factor EF_1

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(percentage of N applied which is emitted as N_2O). The IPCC (Intergovernmental Panel on Climate Change) recommend a "default value" of 1% for N fertiliser and manure EF_1 (IPCC 2006) which has an uncertainty range of 0.3 to 3.0% (Smith et al., 2012). However, there have been a number of international studies reporting lower EF_1 values for urea fertiliser compared to the IPCC default value (e.g. Misselbrook et al., 2014; Kuikman et al., 2006; Velthof and Mosquera, 2011; Galbally et al., 2005; Chen et al., 2010). New Zealand has recently adopted a country specific EF_1 value of 0.48% based on a statistical analysis of animal urine and dung and urea fertiliser field experiments conducted in New Zealand (Kelliher et al., 2014). This country-specific value is based on several studies (e.g. de Klein et al., 2004; Luo et al., 2007, 2010), with about two-thirds conducted in one region of New Zealand (Waikato). For FDE, New Zealand uses a value of 1% (Ministry for the Environment, 2015), which is the same as the current IPCC default value (IPCC, 2006). However, the EF_1 value for FDE could be expected to be lower than the one for urea, as the organic N in FDE is not readily available for nitrification and denitrification, which are the main processes for N_2O production in soil. Another reason why the FDE EF_1 is expected to be lower than 1% is that FDE is a mixture of urine and dung that have New Zealand specific emission factors of 1 and 0.25%, respectively.

A recent increase in the number of studies focusing on determining N_2O emissions and EF_1 values for FDE and urea fertiliser across New Zealand (Li et al., 2014, 2015; van der Weerden and Rutherford, 2015; van der Weerden et al., 2016) provides a timely opportunity to perform a meta-analysis to refine country-specific EF_1 values for these two N sources for New Zealand. Furthermore, Chadwick et al. (2011) suggested that, due to the varying amounts of organic N in animal manure applied to land (in New Zealand's case FDE), it may be more useful to express the N_2O emission factor as percentage of the inorganic N (rather than total N) applied.

The objectives of our study are therefore to firstly utilise the available FDE experimental data to determine the most significant variables influencing FDE EF_1 and to assess the efficacy of expressing the EF1 for FDE as percentage of inorganic N applied; and secondly refine the New Zealand country-specific emission factors for urea fertiliser and FDE.

2. Methodology

2.1. Drivers of FDE EF_1

Access to key soil, climatic and FDE characteristics from Bhandral et al. (2007),Li et al. (2014, 2015), van der Weerden and Rutherford (2015) and van der Weerden et al. (2016) allowed a best subsets regression analysis (Hocking and Leslie, 1967) of their influence on FDE EF_1. A natural log transformation of EF_1 was required due to its non-normal distribution. Because a large fraction of the total N is in the organic form, requiring mineralisation followed by nitrification to form an effluent-derived NO_3^- (Chadwick et al., 2011), we also converted EF_1 to an emission factor based on the readily available N applied, as determined by the total ammoniacal N (TAN) content of the FDE (EF_{1TAN}). The data for EF_{1TAN} was also log transformed (ln) prior to a best subsets regression.

The regression approach examines all possible combinations of variables to determine which combinations give the best prediction of FDE EF_1. Key variables included initial characteristics of the soil (soil pH, soil organic C content, soil total N, soil C:N ratio, soil bulk density), regional/environmental variables (region, season, cumulative rainfall in first 1 and first 3 months, average soil temperature (5 cm depth) in first 1 and first 3 months, average water filled pore space (WFPS) in the first 1 and first 3 months) and effluent characteristics (total solids, pH, Total C, Total N, C:N ratio, TAN content, TAN as a percentage of Total N, TAN and N load). We have used 1 and 3 month periods as we would expect a high proportion (ca 50–80%) of N_2O emissions from FDE to occur in the first month, while emissions can be expected to return to background levels 3–4 months following application (van der Weerden et al., 2016). All data from the studies by Li et al. (2014, 2015), van der Weerden and Rutherford (2015) and van der Weerden et al. (2016) was sourced directly from the publication or, where missing, was provided by the authors. Data from the Bhandral et al. (2007) study was taken directly from the publication's tables and text, or, for average soil temperature and WFPS, was estimated from their figures. Adjusted R^2 values are reported; this measure makes an allowance for the number of parameters used in the best subsets regression. The Akaike information criterion (AIC) was used to guide choice of the best model.

2.2. Meta-analysis of EF_1

Meta-analysis is a quantitative synthesis of results across multiple studies. Kelliher et al. (2014) conducted a meta-analysis of field experimental results to calculate a New Zealand country-specific EF_1 value for urea fertiliser and EF_3 values for cattle and sheep excreta. Their meta-analysis did not include FDE as a source of N_2O, as the available dataset relevant to an EF_1 calculation at that time was limited to a single study in New Zealand: Bhandral et al. (2007). However, the recent increase in field studies on FDE EF_1 (Li et al., 2014, 2015; van der Weerden and Rutherford, 2015; van der Weerden et al., 2016) resulting in the number of FDE EF_1 values increasing 6-fold from 4 to 25, justified a meta-analysis of EF_1 for FDE. For urea, an additional 4 values were available since the Kelliher et al. (2014) meta-analysis, which increased the total data set for urea EF_1 to 24 values. Unlike Kelliher et al. (2014), we did not include urine and dung data (EF_3) for this updated analysis, as the combined dataset of 49 values was considered sufficient for a separate meta-analysis of EF_1.

In total, 49 EF_1 data from 45 field trials were included in the meta-analysis. All field sites were classified according to 2 soil drainage classes (free versus poor), region and season. Trials were limited to four regions of New Zealand (Waikato, Manawatu, Canterbury and Otago), conducted from 2003 to 2015. Season for each trial was defined by determining which month the trial's 15th day occurred as follows: January, February and December for summer, March, April and May for autumn, June, July and August for winter and September, October and November for spring, as previously used by Kelliher et al. (2014).

For estimating EF_1, we used a natural log transformation with N source included as a fixed effect and other effects fitted as random effects within a model that retains any non-zero variance components. The estimated 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_1 values (Kelliher et al., 2014).

3. Results

3.1. Drivers of FDE EF_1

The best subsets regression revealed a significant multi-variable relationship between ln (EF_1) and region, season, soil bulk density, FDE TAN content and Total N load (Adj. $R^2 = 0.74$, $P < 0.001$). The analysis of ln (EF_{1TAN}) produced a similarly significant multi-variable relationship where up to 65% of the variance could be explained by four of the five same variables:

region, season, soil bulk density and FDE TAN content ($P < 0.001$). Adding the 5th term (Total N load) did not improve the regression.

3.2. Meta-analysis of EF_1

Of the 49 values, 26 were obtained in Waikato, 9 in Manawatu, 5 in Canterbury and 9 in Otago. Free draining soils were used for 33 studies, with the remaining 16 studies conducted on poorly drained soils. Most trials were conducted in spring (25), followed by winter (12), autumn (8) and summer (4). The rate of N per application ranged from 13 to 101 kg N ha^{-1} for FDE, while urea fertiliser was generally applied at 50 kg N ha^{-1} apart from two studies where 25 kg N ha^{-1} $application^{-1}$ was used.

The overall mean EF_1 for the combined FDE and urea fertiliser data was calculated as 0.46%, with a lower and upper 95% confidence interval of 0.07% and 0.90% (Table 1). The mean EF_1 values (with the 95% confidence limits in brackets) for urea and FDE were 0.59% (0.14–1.02%) and 0.25% (0.00–0.74%), respectively. The EF_1 values for urea and FDE were not significantly different ($P > 0.05$). Region influenced the overall mean EF_1 ($P = 0.02$), with Manawatu producing the highest EF_1 value of 0.78% (0.36–1.26%) and Canterbury producing the lowest value of 0.18% (0–0.60%) (Table 1). When EF_1 data for the two N sources were analysed separately, there was no significant regional influence on EF_1 ($P > 0.05$). There was no seasonal influence on EF_1 ($P > 0.05$) for either the combined or the separate urea and FDE datasets.

4. Discussion

4.1. Drivers of FDE EF_1: analysis of pooled data

The best subsets regression analysis revealed a significant relationship between EF_1 and five key variables: region, season, soil bulk density, FDE TAN content and total N load. Variation in region, season and soil bulk density reflects the integrated effect of several factors, including soil temperature, rainfall and soil porosity. Rainfall and soil porosity will directly influence soil oxygen supply. Variation in FDE TAN content and total N load reflects the supply of readily available N for microbially-regulated N_2O production and emission. FDE also contains a supply of labile C and a high water content that can lead to anaerobic zones within an aerobic soil immediately after application (Barton and Schipper, 2001; Bhandral et al., 2007). This supply of readily available N and labile C in FDE can lead to high N_2O fluxes within 1 to 3 days of application, as observed in the FDE studies included in our analysis. The TAN content of the FDE used for our analysis ranged widely, from 36 to 1400 mg N L^{-1}.

The five key variables identified in the best subsets regression encompass the proximal regulators of N_2O emission via nitrification and denitrification (temperature, soil oxygen, mineral N and carbon) identified by Tiedje (1988) and de Klein et al. (2001). The analysis explored the influence of each of these variables separately, however the results suggest integration of these variables (and potentially other unidentified variables) was more significant than the separate terms. While this poses the question of what variables have not been identified within the term 'region', it also demonstrates the importance of regional experiments for developing country-specific emission factors.

Because of the combination of TAN and organic N in effluent and manures, it has been suggested that EF_1 may be better represented on the basis of TAN applied rather than total N applied (Chadwick et al., 2011). Our analysis showed that 65% of the variation in EF_{1TAN} could be explained by four variables: region, season, soil bulk density and FDE TAN content. This set of variables is virtually the same as those related to EF_1, apart from the exclusion of total N load, however less variation in EF_{1TAN} could be explained with the tested variables compared to EF_1. This suggests that, for FDE, it would be more appropriate to remain with the current total N applied rather than TAN applied when estimating direct N_2O emissions from land application of managed manure (IPCC, 2006).

4.2. Country-specific EF_1 for urea fertiliser and FDE

A combined urea fertiliser and FDE EF_1 value of 0.46% is approximately half of the current IPCC default value of 1% (IPCC, 2006). The combined dataset revealed a significant regional effect ($P = 0.02$); the best subsets regression analysis of the FDE data also identified region as a significant variable. 'Region' incorporates a multitude of soil and climatic factors that can influence N_2O production and emission, as discussed above. Therefore, when developing country-specific emission factors, there is a need to ensure selected sites and regions adequately represent a country's agricultural soils, climates and farming practices.

4.2.1. Urea

New Zealand's lower mean EF_1 value for urea (0.59%) compared to IPCC's 1% is probably due to the N fertiliser rate. In the experimental studies, N fertiliser was typically applied at 50 kg N ha^{-1} $application^{-1}$, which is similar to the typical rate used for

Table 1
Best linear unbiased predictors (BLUPs) for direct N_2O emission factors (%, mean ± 95% confidence interval, *n*) of two N sources across four regions.

N source	Region	Mean (%)	95% confidence interval (%)
FDE	Waikato	0.26 (11)	0.00–0.67
	Manawatu	0.56 (7)	0.11–1.08
	Canterbury	0.00 (3)	0.00–0.46
	Otago	0.20 (4)	0.00–0.62
	Mean	0.25 (25)	0.00–0.74
Urea fertiliser	Waikato	0.59 (15)	0.32–0.88
	Manawatu	0.92 (2)	0.49–1.41
	Canterbury	0.30 (2)	0.00–0.72
	Otago	0.52 (5)	0.18–0.88
	Mean	0.59 (24)	0.14–1.02
Combined FDE and urea fertiliser EF_1	Waikato	0.46 (26)	0.16–0.79
	Manawatu	0.78 (9)	0.36–1.26
	Canterbury	0.18 (5)	0.00–0.60
	Otago	0.39 (9)	0.06–0.76
	Overall mean	0.46 (49)	0.07–0.90

pasture (ca 30–50 kg N ha^{-1} application^{-1}; Roberts and Morton, 2012). Existing meta-analysis studies have shown lower EF_1 values at low N application rates (e.g. Bouwman et al., 2002; Shcherbak et al., 2014) which may be due to improved N use efficiency (NUE) (Mosier et al., 1998). Most of the urea fertiliser trials were conducted in spring, which is representative of when urea is typically applied to pastures in New Zealand (van der Weerden et al., 2016). Considering the season and rate of N applied in our studies, we suggest that the derived mean EF_1 value for urea fertiliser is representative of common practice on pastoral farms in New Zealand.

Fertiliser form (urea vs NH_4^+-based vs NO_3^--based fertiliser) can also influence the N_2O emissions. For example, Smith et al. (1997) suggested that when soil conditions favor denitrification, nitrate fertilisers produce higher emissions, whereas in dry conditions emissions from urea or NH_4^+-based fertilisers were higher. Kuikman et al. (2006) analysed N_2O measurements taken across the Netherlands, and concluded that N_2O emissions were greater from NO_3^--based fertilisers than from NH_4^+-based fertiliser and urea due to the former providing a more readily available mineral N pool for denitrification. Smith et al. (2012) reported on a UK-wide series of field experiments comparing N fertiliser forms, where there was evidence of lower emissions from urea. This may have also been partly due to losses of NH_3 following rapid urea hydrolysis, which can reduce the net amount of N remaining in the soil as a potential source of N_2O (van der Weerden et al., 2016).

There have been several international studies reporting lower EF_1 values for urea and NH_4^+-based fertilisers compared to the IPCC (2006) guidelines default value of 1%. Misselbrook et al. (2014) reported on a series of UK experiments, where the mean EF_1 for urea and ammonium nitrate fertiliser, applied at rates of between 40 and 80 kg N ha^{-1}, was 0.47% and 0.80%, respectively. The Netherlands has adopted an EF_1 of 0.5% for urea and NH_4^+-based fertilisers applied to mineral soils (Kuikman et al., 2006; Velthof and Mosquera, 2011). While Australia continues to adopt an EF_1 value of 1.0% for N fertiliser, studies on Australian pasture have produced urea fertiliser EF_1 values of 0.47% and 0.50% (Galbally et al., 2005; Chen et al., 2010).

New Zealand currently uses a country-specific urea EF_1 value of 0.48%, based on a meta-analysis of urine, dung and urea fertiliser data (Kelliher et al., 2014). Our revised meta-analysis of urea EF_1 did not include the influence of urine and dung data, but included the influence of FDE EF_1 data, which was found to be similar to urea. Our results suggested a revised urea EF_1 mean of 0.59%, which was greater than the result from Kelliher et al. (2014) of 0.48% for two reasons: (1) the effect of 4 additional data values from the current study and (2) the effect of a bias correction on the EF_1 means with and without excreta EF_3 data. The bias correction was applied to both analyses (Kelliher et al., 2014 and the current study) to ensure ratios of the estimated EF means between N sources have been conserved.

4.2.2. Farm dairy effluent

The most common type of manure applied to land in New Zealand is FDE (Laubach et al., 2015), with the majority of stored FDE typically applied from spring through to mid-summer, with less applied in the latter half of the lactation season up to the end of autumn to ensure FDE storage ponds are empty by the beginning of winter (Dave Houlbrooke, AgResearch, pers. comm.). The N load of FDE is typically between 30 and 150 kg N ha^{-1} (maximum N load; Houlbrooke et al., 2013), while the N loads used in the research trials ranged from 13 to 101 kg N ha^{-1}. With the absence of a seasonal effect on EF_1, our calculated mean FDE EF_1 value of 0.25% can be regarded as representative of typical farm activity.

Farm dairy effluent is more dilute with a lower N content compared to the slurries commonly applied to soil in the Northern Hemisphere (Laubach et al., 2015). However, EF_1 values for application of FDE and slurry to pastoral soils appear to be similar. Velthof and Mosquera (2011) surface applied cattle slurry to grassland over three years at an equivalent rate of between 274 and 332 kg N ha^{-1}, resulting in EF_1 values of between 0 and 0.2%, averaging 0.1%. Misselbrook et al. (2014) applied cattle slurry to grassland in four experiments, where application rates ranged from 106 to 181 kg N ha^{-1}. Three of the experiments resulted in EF_1 values of between 0.04% and 0.23%, while 1.15% was measured in the remaining experiment. Bourdin et al. (2014) conducted a study in Ireland, where grass-fed cattle slurry was applied to grassland on 4 occasions from spring to summer to determine if EF_1 was affected by total solids (TS) content. Slurry was applied at an equivalent rate of between 26 and 67 kg N ha^{-1}, which lies within the range of FDE N loads used in New Zealand studies (13–101 kg N ha^{-1}; Bhandral et al., 2007; Li et al., 2014, 2015; van der Weerden et al., 2016). Bourdin et al. (2014) found that TS content, which ranged from 3.3 to 6.3%, had no significant effect on EF_1, which averaged 0.67% across the 4 slurry applications. However, the TS of the FDE data used for our meta-analysis was lower, ranging from 0.02 to 2.80% (data not shown). Dilute manures such as FDE will infiltrate to greater depths when moderate to large soil moisture deficits are present. This may partly explain why the Irish study produced an EF_1 value 2.5 times higher than our mean FDE EF_1 value of 0.25%.

We found that while there was no significant difference between urea fertiliser EF_1 and FDE EF_1 at the 5% level, the FDE mean was substantially lower. Approximately 50% of the total N in FDE is in the organic form with the remaining N as ammonium (Laubach et al., 2015). In contrast, as N in urea fertiliser is 100% readily available, it may be possible that the NUE of FDE is slightly greater than urea when applied at similar total N loadings due to an overall slower supply of FDE N to the soil-plant system. Increased NUE may reduce the risk of N losses including N_2O (Powell and Rotz, 2015). This difference in N composition may explain the (non-significant) difference in EF_1 means for these two N sources. A recent study included a direct comparison of both N sources in four regions of New Zealand (van der Weerden et al., 2016), which showed the mean EF_1 for urea was approximately double that for FDE. Both N forms were applied at similar rates (30–50 kg N ha^{-1}), and therefore the difference in EF_1 was unlikely to be related to N loading rate. Considering FDE is a mixture of urine and dung, with corresponding New Zealand country-specific emission factors of 1% and 0.25% (Ministry for the Environment, 2015), and this mixture is diluted with water, one could expect the mean FDE EF_1 would be less than 1%.

To calculate the most accurate New Zealand agricultural soils N_2O emissions inventory, we recommend separate country-specific EF_1 means are used for FDE and urea fertiliser. We also recommend the EF_1 means are truncated to one decimal place, recognising the large confidence intervals. On this basis, we recommend New Zealand adopts an EF_1 mean of 0.3% for FDE and 0.6% for urea fertiliser.

5. Conclusions

A best subsets regression analysis revealed a significant relationship ($R^2 = 0.74$; $P < 0.001$) between FDE EF_1 five key variables: region, season, soil bulk density, FDE TAN content and total N load. The regression analysis with EF_{1TAN} showed that less variation could be explained compared to EF_1. This suggests that, for FDE, it would be more appropriate to continue to express EF_1 as percentage of total N rather than TAN applied. The meta-analysis of FDE-EF_1 ($n = 25$) and urea fertiliser- EF_1 data ($n = 24$) from New

Zealand studies has shown that an overall country-specific EF_1 mean was 0.46% ($n = 49$) with a corresponding 95% confidence interval of 0.07% and 0.90%. However, separate country-specific EF_1 means were 0.3 and 0.6% for FDE and urea fertiliser, respectively. We recommend these two values are employed within New Zealand's agricultural greenhouse gas inventory due to the different origin and characteristics of these N sources. Finally our analyses demonstrated the need for adequate representation of a country's soils, climate and farming systems for developing country-specific emission factors.

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