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The uncertainty of nitrous oxide emissions from grazed grasslands: A New Zealand case study

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HIGHLIGHTS

- Uncertainty estimated for New Zealand's pastoral agricultural N_2O emissions inventory.
- Emission factor uncertainty estimated by meta-analysis results from 185 field trials.
- Results from new analytic method compared well with Monte Carlo numerical simulation.
- For independent variables and 95% confidence, inventory uncertainty averaged ±58%.

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ABSTRACT

Agricultural soils emit nitrous oxide (N_2O), a greenhouse gas and the primary source of nitrogen oxides which deplete stratospheric ozone. Agriculture has been estimated to be the largest anthropogenic N_2O source. In New Zealand (NZ), pastoral agriculture uses half the land area. To estimate the annual N_2O emissions from NZ's agricultural soils, the nitrogen (N) inputs have been determined and multiplied by an emission factor (EF), the mass fraction of N inputs emitted as N_2O–N. To estimate the associated uncertainty, we developed an analytical method. For comparison, another estimate was determined by Monte Carlo numerical simulation. For both methods, expert judgement was used to estimate the N input uncertainty. The EF uncertainty was estimated by meta-analysis of the results from 185 NZ field trials. For the analytical method, assuming a normal distribution and independence of the terms used to calculate the emissions (correlation = 0), the estimated 95% confidence limit was ±57%. When there was a normal distribution and an estimated correlation of 0.4 between N input and EF, the latter inferred from experimental data involving six NZ soils, the analytical method estimated a 95% confidence limit of ±61%. The EF data from 185 NZ field trials had a logarithmic normal distribution. For the Monte Carlo method, assuming a logarithmic normal distribution for EF, a normal distribution for the other terms and independence of all terms, the estimated 95% confidence limits were −32% and +88% or ±60% on average. When there were the same distribution assumptions and a correlation of 0.4 between N input and EF, the Monte Carlo method estimated 95% confidence limits were −34% and +94% or ±64% on average. For the analytical and Monte Carlo methods, EF uncertainty accounted for 95% and 83% of the emissions uncertainty when the correlation between N input and EF was 0 and 0.4, respectively. As the first uncertainty analysis of an agricultural soils N_2O emissions inventory using "country-specific" field trials to estimate EF uncertainty, this can be a potentially informative case study for the international scientific community.

1. Introduction

In soils, nitrogen (N) containing compounds can be transformed to produce nitrous oxide (N_2O), the third most important greenhouse gas (Davidson and Kanter, 2014). In addition, N_2O is the primary source of nitrogen oxides which deplete stratospheric

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ozone (Ravishankara et al., 2009). Agriculture has been considered the largest source of anthropogenic N_2O emissions and estimated to account for about 70% of the total (Davidson and Kanter, 2014). Pastoral agriculture is practised across 30% of the world's land area, one-third of cropping land area produces animal feed and the world's estimated animal feed N_2O emissions range from 4.4 to 6.8 Tg/y (Herrero et al., 2016). Consequently, the N_2O emissions from pastoral agriculture are substantial, but uncertain.

The N_2O emissions from soils can be attributed to the effects of N inputs (de Klein et al., 2006, 2014a). For pastoral agriculture, the N inputs include N in fertiliser and the urine and dung excreted by grazing animals. The mass fraction of N input emitted from soils as N_2O-N has been denoted an emission factor (EF). Consequently, the N_2O emissions can be estimated by a product of N input and EF. This method includes an inventory of N inputs and EFs following guidelines developed by the Intergovernmental Panel on Climate Change (IPCC, http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf) for signatory nations to the United Nations Framework Convention on Climate Change (UNFCCC).

For the UNFCCC, inventories estimate N_2O emissions across national and annual scales. While N_2O emissions can only be measured at smaller scales, the generalisation of such observations can be the basis for an inventory. Information about the spatial and temporal variability or uncertainty of emission measurements can be informative. For example, 'hot spots' have had a large N input such as urine excreted by grazing animals (Selbie et al., 2015). For grazed areas, hot spots have been found to be the primary source of N_2O emissions (e.g., Kelliher et al., 2002; Giltrap et al., 2014). The temporal variation of N_2O emissions can be dominated by 'hot moments' (Groffman et al., 2009). For example, over 242 days, half the total emissions from grazed pasture comprised three 'events' over 16 days (Scanlon and Kiely, 2003). Following N input, the variability of N_2O emissions has been related to soil wetness which depends on rainfall and irrigation (van der Weerden et al., 2012, 2014).

Ideally, an inventory compiler has accurate and representative information to estimate the emissions. Inventory uncertainty can be estimated by statistically analysing the input information and output calculations (Winiwarter and Muik, 2010). Monte Carlo numerical simulation has been a method used to estimate the uncertainty of agricultural soil N_2O emissions inventories (Winiwarter and Rypdal, 2001; de Vries et al., 2003; Ramirez et al., 2008; Milne et al., 2014). For this method, a set of input data has been determined by sampling from estimated frequency distributions and the inventory computations repeatedly undertaken to calculate an output uncertainty statistic such as 95% confidence limits. Alternatively, provided the inventory can be represented by a suitable mathematical function and input variable statistics estimated, the output uncertainty statistics can be estimated by an analytical method (e.g., Kelliher et al., 2007; Kelliher and Clark, 2010).

Analysing inventory uncertainty can provide information about which factors contribute most to the variability or uncertainty of the output calculations. While as implied, for accuracy and representativeness, the inputs should be determined empirically by a large number of measurements, we are aware of no studies which have taken this approach for a national, annual inventory of agricultural soils N_2O emissions. For those analysing the uncertainty of such inventories, a noticeable stumbling block has apparently been the lack of sufficient "country-specific" EF data. Moreover, to our knowledge, the correlation of N input and EF variables has not been determined empirically due to a lack of sufficient "country-specific" data. In New Zealand (NZ), half the land area is used for pastoral agriculture. Thus, pastoral agriculture is not only vitally important to NZ's economy, it is also a major driver of NZ's greenhouse gas emissions including the agricultural soils N_2O emissions inventory. For these reasons, in NZ, information about pastoral agriculture is important and available. Consequently, predicated on sufficient "country-specific" data, analysing the uncertainty of NZ's agricultural soils N_2O emissions inventory can be a potentially informative case study for the international scientific community.

For this paper, an analytical method will be developed to estimate the uncertainty of an inventory representing NZ's agricultural soil N_2O emissions. Estimates will also be made using the Monte Carlo method and results from the two methods will be compared. While estimating N input uncertainty will have to rely on expert judgement, EF uncertainty will be estimated by meta-analysis of the results from 185 NZ field trials (Kelliher et al., 2014a). As will be shown, while a correlation between N input and EF affects the inventory's uncertainty, inventory-scale data were not available to estimate the correlation. Instead, the correlation will be inferred by meta-analysis of replicate-level results from experiments involving six NZ soils (de Klein et al., 2014b; Kelliher et al., 2014b; Venterea et al., 2015). The estimated uncertainty of NZ's inventory will be compared with estimates for inventories from other countries.

2. Material and methods

The N_2O emissions from agricultural soils (E_{N_2O}) can be estimated by a product of N input and a representative value of EF. For N input, we need to estimate the annual mass of N returned by the excreta of grazing animals which includes dairy and beef cattle, sheep and deer. Thus, we need to determine the number of animals, a, and mean values of the animal's annual energy requirement (d, MJ animal^{-1} y^{-1}), the pasture (feed) energy content (e, MJ kg^{-1} [dry matter] = MJ kg^{-1} DM), the pasture N content, p_N, and the fraction of N that will be retained in an animal, r_N. We combined these terms as $\left[a\,d\left(\frac{1}{e}\right)p_N(1-r_N)\right]$. In addition, we need to estimate the annual mass of N fertiliser applied to agricultural soils across NZ, most commonly as urea and denoted by term u. An E_{N_2O} equation was then be written as:

$$E_{N_2O} = \left\{\left[a\,d\left(\frac{1}{e}\right)p_N\,(1-r_N)\right]+u\right\}\left(\frac{44}{28}\right)EF \tag{1}$$

Using the N_2O/N_2 molecular mass ratio (44/28 = 1.57), units on the right hand side of the equation were converted from Gg N y^{-1} and E_{N_2O} expressed as Gg N_2O y^{-1}.

For uncertainty analysis, we used data from NZ's E_{N_2O} inventory for the year 2014 (Ministry for the Environment, 2016). As shown below, the quantity (a d) needs to be 585 × 10^9 MJ y^{-1}. For this purpose, the mean values of p_N, r_N and e will be 0.035 (kg N kg^{-1} DM), 0.15 and 11 MJ kg^{-1} DM, respectively (Kelliher et al., 2007). By inserting these 4 values into $\left[a\,d\left(\frac{1}{e}\right)p_N(1-r_N)\right]$, we calculated 1582 Gg N y^{-1} the value used for NZ's 2014 inventory. Based on N fertiliser sales, u will be 377 Gg N y^{-1} (Ministry for the Environment, 2016). The NZ inventory also accounts for E_{N_2O} from managed excreta attributed to dairy cattle during milking, crop residues and cultivated organic soils. For the year 2014, these totalled 1.5 Gg N_2O (Ministry for the Environment, 2016). This quantity will be added to the result of the calculation using Equation (1).

To determine a representative EF value, we combined the urine,