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Spatial and temporal nitrous oxide emissions from dairy cattle urine deposited onto grazed pastures across New Zealand based on soil water balance modelling

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ABSTRACT

Nitrous oxide emissions from urine deposited onto soils during grazing are captured within the New Zealand national inventory by employing an annual average country-specific emission factor (EF_3) of 1%. However, soil moisture is a key driver of N_2O emissions, and we propose a soil water balance model can be used to determine spatially- and temporally-disaggregated emission factors to refine and improve the emissions estimate. We constructed a GIS-based water balance model that operates on regional and monthly scales and developed a predictive relationship between soil water content and EF_3. Combined with estimated monthly cattle urine excretion, we calculated annual N_2O emissions for four years, ranging between 6.6 and 7.5 Gg y^{-1}. The associated, annual mean EF_3 value was 0.9–1.0%. This is very similar to the currently employed country-specific EF_3 value, which results in an annual N_2O emission of 7.0–7.7 Gg y^{-1}. Within-year variability in regional and monthly EF_3 was much greater than the between-year variability in country-wide annual average EF_3, reflecting a strong averaging affect across temporal and spatial scales.

1. Introduction

In New Zealand, the primary source of N_2O emissions come directly from soils following excreta deposition by farmed, grazing ruminants, representing 57% of the total emissions (Ministry for the Environment, 2013). Emissions from urine patches are most important due to the excessive supply of mineral nitrogen (N) in a small concentrated area. Under urine patches, N_2O fluxes will not be limited by N substrate supply. Instead, N_2O production will be primarily influenced by soil water content (Linn and Doran, 1984) with denitrification being the dominant process regulating emissions from New Zealand pastoral soils (Müller and Sherlock, 2004). Emissions have previously been related to soil water content for N fertiliser applied to grassland (Dobbie and Smith, 2003) and, using a limited dataset, dairy urine deposited on pasture (van der Weerden et al., 2011).

The majority of national nitrous oxide (N_2O) inventories submitted by countries that have ratified the United Nations Framework Convention on Climate Change (UNFCCC) employ the IPCC's (Intergovernmental Panel on Climate Change) Tier 1 method (IPCC, 2001). This method requires a knowledge of activity data for each N source (e.g. amounts of artificial N fertiliser applied to soil and excreta-N deposited by farmed animals during grazing of pasture and rangelands) and an associated emission factor (EF), i.e., the percentage of applied N lost as N_2O to the atmosphere (IPCC, 2001). The IPCC Tier 1 method yields a summed, annual figure which is deemed suitable for minor sources contributing to national inventories. However, while accurate and credible national inventories are necessary for advancing emission reduction efforts (Smith et al., 2007), this cannot be fully achieved by using default emission factors (Berdanier and Conant, 2012) due to the inability of the Tier 1 methodology to describe the biophysical processes regulating N_2O emissions. For substantial N_2O sources, countries should consider adopting a higher tier approach (e.g. Tier 2) to provide more accurate

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estimates. A Tier 2 approach may include disaggregation of the EF to separately account for key sources and these EF values can be inferred or estimated from other known variables. An example of a disaggregated approach is New Zealand's current inventory, where the EF for excreta deposited during pasture grazing (EF_3) is disaggregated into urine and dung (these EF_3 values are averages from field trial measurements and equal to 1% and 0.25%, respectively; Ministry for the Environment, 2013). An example of an inferred EF approach is the recent work by Lesschen et al. (2011) where annual EF values were estimated using key variables including N source, soil type, land use and rainfall and implemented in a large-scale model for predicting N_2O emissions from European agricultural soils.

An alternative Tier 2 approach accounts explicitly for spatial and/or temporal variation when estimating the N_2O emissions from different land uses across a country (Lilly et al., 2009; Dalgaard et al., 2011; Duretz et al., 2011). Lilly et al. (2009) used a spatial approach for estimating annual N_2O emissions across Scotland based on a soil wetness estimate, accumulated temperature and emissions data for each agricultural source including N fertiliser use, grazed and ungrazed pastures, crop production and woodlands. Duretz et al. (2011) developed a much smaller spatial (25 m by 25 m, applied to a simplified 1.75 km by 1.75 km mixed crop and pig farming landscape integrated across a landscape) and temporal (daily time step) scale model that integrates four existing models simulating atmospheric, farm, agro-ecosystem and hydrological reactive N fluxes and transformations. Dalgaard et al. (2011) used a set of inventory-type equations to estimate the variability of annual emissions from 56 pig, dairy cattle and crop farms located in an 84 km^2 landscape, noting that for their calculations, the annual, landscape-scale emissions calculated as a sum of the farm-scale emissions differed from a landscape-scale calculation using averages of the input data from the 52 farms. Thus, spatial approaches provide increased refinement of inventory calculations including source and location of the N_2O emissions. When coupled with knowledge of temporal variability, spatial approaches allow assessment of the effects of climate variation (e.g. drought vs. flooding), land use changes and on-farm practices on estimated N_2O emissions. Utilising activity data within a spatial/temporal approach would allow national inventories to be responsive to climate variability. For example, variation in livestock N excretion rates due to significant drought would be captured. Disaggregation of national inventories may also create opportunities for capturing the effects of mitigation strategies that target key temporal periods and/or regions within a country, and predicting climate change impacts on future N_2O emissions.

The objective of the current study was to explore the relationship between soil water content and N_2O emissions in the context of a national N_2O emissions inventory, and develop a GIS-based spatial soil water balance model to estimate the N_2O emissions from dairy urine deposited onto dairy pastures. One of our key aims was to avoided complicated computations, thereby making it a practical approach for estimating national and regional N_2O emissions across the year with sufficient temporal responsiveness to individual rainfall and drainage events. To our knowledge, this has not been done previously to estimate national, annual N_2O emissions from the excreted urine and presently, New Zealand's dairy cattle population can be up to ~7 M during the spring, calving season. Furthermore, New Zealand's activity data and inventory calculation provides monthly excreta data, so the temporal (monthly) variation in emissions can be estimated, providing insight into within-year variation in N_2O emissions as affected by climate and excreta variability. A combined spatial and temporal approach will provide a refinement and improvement to estimating national N_2O emissions.

2. Methods

2.1. Overall approach

N_2O emissions from dairy urine deposited onto dairy pastures across New Zealand was estimated spatially and temporally by (i) developing and testing a soil water balance model, (ii) translating the model into a geographic information system (GIS) to be driven by daily rainfall and evaporation data, (iii) determining the efficacy of predicting EF_3 from soil water content, based on either volumetric water content (θ; $m^3\,m^{-3}$) or water filled pore space (WFPS; %), and (iv) deployment: combining the spatial and temporal estimates of EF_3 with the regional, monthly estimates of dairy cattle urine excretion to estimate the effect of soil water variability on monthly and annual N_2O emissions (Fig. 1). The estimated emissions for four years of calculations were compared with those calculated according to New Zealand's current national N_2O inventory approach (Ministry for the Environment, 2013).

2.2. Developing and testing a soil water balance model

Soil water was represented by θ, which depends on a net balance of rainfall, drainage and evaporation. Annual rainfall varies significantly across New Zealand and at specific locations from one year to another. For example, for the years 1905–1980 at Ruakura, Hamilton, the annual rainfall ranged from 840 to 1640 mm with a mean of 1201 mm. The fate of rainfall onto soils depends on the drainage rate. Across New Zealand, 75% of the pastoral soils' area was classed as freely-drained, while 17 and 9% are imperfectly and poorly drained, respectively (Sherlock et al., 2001). Daily potential evapotranspiration (PET) from well-watered pasture can be estimated using solar radiation, soil temperature and wind speed measurements made at weather stations across New Zealand. Based on this premise and using daily rainfall and PET data interpolated from virtual climate stations across New Zealand (Tait and Woods, 2007; Tait et al., 2006), a spatial and temporal soil water balance model was constructed which estimated θ in the uppermost 400 mm at a 500 × 500 m scale. Virtual climate stations are points across the landscape at a 5 × 5 km scale where climate data has been determined by interpolation from the data of physical climate stations. As stated, the model depends on accurate estimation of the drainage rate to estimate θ on a daily basis. Following Kelliher et al. (2005), a drainage algorithm simulates the daily rate of drainage and surface runoff in soils. It was assumed that drainage of water in the soil is determined by gravity at a rate that is uniform with depth. Using the relationship developed by Campbell (1985), we determined that

$$K = K_s\left(\frac{\theta}{\theta_s}\right)^m = -Z\frac{d\theta}{dz} \qquad (1)$$

where K = hydraulic conductivity (mm day^{-1}), K_s = saturated hydraulic conductivity (mm day^{-1}), θ_s = porosity or satiated water content ($m^3\,m^{-3}$), m = dimensionless power coefficient, Z = depth of soil from which drainage is occurring (mm) and z = depth in the soil (mm). Using Eq. (1) with a daily time (t) interval (that is, over time from t_1 to t_2), K will change during the day when the soil is wet (that is, over time from θ_1 to θ_2). Separating variables in Eq. (1) and integrating gives

$$\frac{K_s}{Z}\int_{t_1}^{t_2} dt = -\int_{\theta_1}^{\theta_2}\left(\frac{\theta^{-m}}{\theta_s}\right)d\theta \qquad (2)$$