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Nitrous oxide emission sources from a mixed livestock farm

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ABSTRACT

The primary aim of this study was to identify and compare the most significant sources of nitrous oxide (N_2O) emissions from soils within a typical mixed livestock farm in Scotland. The farm area can be considered as representative of agricultural soils in this region where outdoor grazing forms an important part of the animal husbandry. A high temporal resolution dynamic chamber method was used to measure N_2O fluxes from the featureless, general areas of the arable and pasture fields (general) and from those areas where large nitrogen additions are highly likely, such as animal feeding areas, manure heaps, animal barns (features). Individual N_2O flux measurements varied by four orders of magnitude, with values ranging from −5.5 to 80,000 μg N_2O-N m^{-2} h^{-1}. The log-normal distribution of the fluxes required the use of more complex statistics to quantify uncertainty, including a Bayesian approach which provided a robust and transparent method for "upscaling" i.e. translating small-scale observations to larger scales, with appropriate propagation of uncertainty. Mean N_2O fluxes associated with the features were typically one to four orders of magnitude larger than those measured on the general areas of the arable and pasture fields. During warmer months, when widespread grazing takes place across the farm, the smaller N_2O fluxes of the largest area source – the general field (99.7% of total area) – dominated the overall N_2O emissions. The contribution from the features should still be considered important, given that up to 91% of the fluxes may come from only 0.3% of the area under certain conditions, especially in the colder winter months when manure heaps and animal barns continue to produce emissions while soils reach temperatures unfavourable for microbial activity (< 5 °C).

1. Introduction

Nitrous oxide (N_2O) is a powerful greenhouse gas, which also contributes to stratospheric ozone depletion (Intergovernmental Panel on Climate Change, 2014; Ravishankara et al., 2009). Microbially mediated nitrification and denitrification pathways in soils and aquatic environments are the primary sources of N_2O (Butterbach-Bahl et al., 2013; Davidson et al., 2000). The increase in livestock numbers (Thornton, 2010) and large-scale application of nitrogen fertilisers to agricultural soils over the past 100 years have contributed to large increases in concentrations of reactive nitrogen in the environment (Fowler et al., 2013). This has resulted in a significant increase in anthropogenic N_2O emissions at a global scale (Reay et al., 2012).

Quantifying agricultural N_2O emissions at large scales have proven difficult due to the uncertainties involved in measuring N_2O fluxes (Cowan et al., 2015; Giltrap et al., 2014; Mathieu et al., 2006), the multiple environmental factors which influence N_2O production at a microbial level (Butterbach-Bahl et al., 2013; Thomson et al., 2012) and in accounting for the effects of a wide variety of farm management practices which alter the natural nitrogen cycle. The complex heterogeneous nature of agricultural soils presents a challenge when it comes to identifying which microbiological processes (i.e. denitrification, nitrifier denitrification, chemodenitrification, nitrification) are contributing to N_2O emissions. These processes may occur simultaneously within microsites of the same soil (Baggs, 2008), the rates of which may be independently controlled by a multitude of different environmental factors (e.g. temperature, soil moisture content, availability of organic carbon) (Bateman and Baggs, 2005; Davidson, 1992). The availability of mineralised nitrogen (predominantly ammonium NH_4^+ and nitrate NO_3^-) is known to be a significant driver of N_2O production from agricultural soils, but this relationship is unpredictable and can be influenced significantly by a wide spectrum of spatial and temporal environmental variables (Cowan et al., 2015; Kim et al., 2013; Shcherbak et al., 2014).

Previous experiments have been carried out with the goal of quantifying N_2O emissions from individual farms with some success (Brown et al., 2001; Ellis et al., 2001; Flessa et al., 2002; Velthof and Oenema, 1997). Due to the complexity and magnitude of the task, these

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studies often focus on a particular aspect of N_2O emissions from agricultural sources such as animal waste management (Chadwick et al., 1999), fertiliser use (Brown et al., 2001; Ma et al., 2010) or secondary emissions caused by leaching losses from soils (Reay et al., 2009). Lesser quantified sources of N_2O such as ditches, gateways and feeding troughs are also potentially large emitters (Cowan et al., 2015; Matthews et al., 2010), but are not always accounted for in current N_2O inventories due to a lack of available measurement data. In order to effectively manage and mitigate agricultural emissions of N_2O it is important to understand both the magnitude of emissions from different sources at the farm scale and to identify the most significant drivers of variation in N_2O flux between these sources. Better identification and quantification of high N_2O flux sources may increase our ability to mitigate farm scale emissions by identifying simple farm management practices that have a positive impact.

The vast majority of studies into agricultural sources of N_2O have used chamber methodology to measure fluxes. These measurements typically show a highly skewed, approximately log-normal distribution, with a small number of very high values (Cowan et al., 2015; Folorunso and Rolston, 1984; Velthof et al., 1996; Yanai et al., 2003). To infer the total flux from a whole field (i.e. the population of interest which has been sampled), the integral of the estimated log-normal distribution over the field is simply given by the mean flux (μ) multiplied by the area of the field. However, μ is poorly estimated by the arithmetic mean of the samples, because of its sensitivity to outliers. μ is therefore often highly uncertain, but estimating the uncertainty in the arithmetic mean of log-normally distributed data is problematic (Land, 1972). The density of a log-normally-distributed variate, x, is given by:

$$d = 1/(\sqrt{(2\pi)}\sigma_{log}x)exp(-((log(x) - \mu_{log})^2/(2\sigma_{log}^2))) \quad (1)$$

where $\mu_{\log}$ and $\sigma_{\log}$ are the mean and standard deviation of the log-transformed variate. The mean of the distribution (i.e. without log transformation) is given by:

$$\mu = \exp(\mu_{log} + 0.5\sigma_{log}^2) \quad (2)$$

Estimates of the parameters of the underlying log-normal distribution, $\mu_{\log}$ and $\sigma_{\log}$ (and thereby the true value of μ), are often poor because of small sample size, measurement error and large variability. In order to better predict fluxes at the field or farm scale we therefore need a sound method for quantifying the uncertainty in μ which arises in estimating whole-field-scale fluxes from a small, log-normally distributed sample. Several methods have been proposed previously for calculating confidence intervals for the mean of a log-normally distributed variable (El-Shaarawi and Lin, 2007; Land, 1972; Parkin et al., 1990). However, with small sample sizes and/or large variability, these methods are often unsatisfactory, and can result in implausibly large intervals (Zou et al., 2009).

The primary aim of this study was to identify and compare the most significant sources of N_2O emissions from a typical livestock farm in Scotland, with a focus on N_2O emissions from sources which are not associated directly with nitrogen fertiliser application, since the latter are already well-documented. A secondary aim was to examine the chemical properties of the soils in locations from which flux measurements were made in order to explain the variability in N_2O emissions across the wide range of soil environments sampled across the farm. Our third aim was to investigate methods for upscaling point measurements to estimate whole-farm emissions and the associated uncertainties using a Bayesian approach.

2. Materials and methods

2.1. Farm description

The Easter Bush Farm Estate is a combination of several farms near Penicuik, Midlothian in Central Scotland (55° 51' 55.7036"N, 3° 12' 44.3549"W). These farms are owned by either by Scotland's Rural College (SRUC) or the University of Edinburgh (UoE) and are run for commercial and research purposes. A selection of twenty separate fields where chosen which represented the wide variety of management practices within the estate and which were readily accessible for our flux measurement equipment. These fields covered approximately 133 ha of land and were chosen to represent a typical Scottish livestock farm in this study (Table 1). Fields were either used for growing arable crops for fodder (barley, oilseed rape, or silage grass) or as grazing pasture for sheep or cattle. The farm managers at the estate estimated that the selected fields and sheltered barns would provide for 440 ewes with 835 lambs and 86 cattle with 60 calves over the period of a year. The perimeter and area of each field was measured manually using a handheld GPS device (Garmin eTrex Legend HCx, Garmin, Shaffhausen, Switzerland).

Table 1
A description of seasonal management of the each of the fields selected to represent the livestock farm in this study.

Field Name	Area (ha)	Autumn 2012	Winter 2012/2013	Spring 2013	Summer 2013
Corner Field	6.72	Sheep	Sheep	Sheep	Sheep
Engineers Field	5.30	Sheep	Sheep	Sheep	Sheep
Middle Field	5.44	Cattle	Sheep	Sheep	Sheep
Paddock Field	4.08	Sheep	Sheep	Sheep	Sheep
Bog Hall Field	7.55	Barley	Empty	Barley	Barley
Kimming Hill	12.16	Silage	Sheep	Silage	Silage
Anchordales	2.67	Barley	Empty	Barley	Barley
Anchordales N.L.T	5.36	Barley	Empty	Barley	Barley
Cow Loan	4.79	Barley	Empty	Barley	Barley
Hay Knowes	10.92	Barley	Oilseed	Oilseed	Barley
Crofts	8.67	Barley	Empty	Barley	Barley
Low Fulford	7.72	Silage	Sheep	Silage	Silage
Fulford Camp	5.37	Sheep	Sheep	Sheep	Sheep
Mid Fulford	9.57	Cattle	Empty	Sheep	Sheep
Fulford Stackyard	3.68	Sheep	Sheep	Sheep	Sheep
Upper Fulford	4.48	Sheep	Empty	Cattle	Cattle
Nuek	4.89	Cattle	Empty	Cattle	Cattle
Doo Brae	5.76	Sheep	Sheep	Cattle	Cattle
Woodhouselee Camp	4.94	Cattle	Cattle	Cattle	Cattle
Lower Terrace	12.56	Barley	Empty	Empty	Sheep

2.2. Quantification of N_2O source area coverage

Using GPS measurements, we estimated the total area coverage of each of the arable and grazed fields each season to within ± 10%. The area coverage of the farm was fairly evenly split between arable and grazing use (Table 2). Some of the larger grass fields were switched between livestock grazing and silage grass (arable) for several months at a time (see Table 1). Cattle were moved between barns and pasture, whereas the sheep spent all year round in the fields. Our measurements covered the general grazed grasslands and arable fields, and several smaller features which we identified as potentially important sources of N_2O. These features were areas of the farm which were used more intensively, and comprised: areas around animal feeding and drinking troughs; areas that had recently been used for manure storage; disturbed areas e.g. near gates or recently tilled; manure heaps; the concrete-floored barns which accumulated animal waste; and silage heaps. Calculation of the areas of these features was more uncertain. For example, a single manure heap and surrounding area contaminated by the heap covered an area of 532 m^2, but the relative proportions changed seasonally as the heap grew in size (up to 3 m high) and was spread onto arable crops in autumn. The capacity of the bedding area of the animal barns was ~2500 m^2, but the area used by the cattle varied seasonally. This was relatively high in the autumn and winter months (60–80%) and lower for the rest of the year (~20%). The silage heap