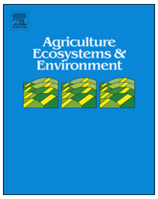
Agriculture, Ecosystems and Environment 268 (2018) 171–180

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee



Nitrous oxide fluxes determined by continuous eddy covariance measurements from intensively grazed pastures: Temporal patterns and environmental controls

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ARTICLE INFO

Keywords:
Nitrous oxide
Eddy covariance
Water-filled pore space
Nitrification
Denitrification
Grazed pastures

ABSTRACT

Nitrous oxide (N_2O) is a prominent greenhouse gas. Our understanding of environmental controls on N_2O fluxes has mainly come from small-scale experiments, for example, static chamber measurements on plots or lab incubations. However, studies of the environmental controls for N_2O fluxes at ecosystem scales have been limited. Using eddy covariance (EC) measurements, this study evaluated the environmental drivers of N_2O fluxes for a one-year period at a farm grazed year-round by dairy cows in the Waikato region, New Zealand. We identified an optimum soil moisture/temperature zone that favours maximal N_2O emissions, demonstrating maximum N_2O fluxes at ~70% water-filled pore space (WFPS) and moderate soil temperatures. Our measurements consistently identified significant N_2O flux pulses associated with rainfall following grazing events in warm-dry months. In contrast, during cold-wet months when WFPS was consistently high, pulses after rainfall did not occur. A clear positive temperature response for N_2O fluxes was observed above 70% WFPS while a negative relationship was detected when WFPS was less than 70%. Distinctive diurnal flux patterns emerged in both pulses and background fluxes, implying that soil temperature regulates N_2O fluxes at sub-daily timescales. Over the annual period, N_2O emissions were 6.5 kg N_2O-N ha^{-1}. We found the highest cumulative rates (maximum 35.7 g N_2O-N ha^{-1} day^{-1}) in autumn but the rates were low during both summer and winter. Our results highlighted the combined effects of environmental factors on N_2O fluxes, and quantified N_2O flux variations at seasonal and daily scales, suggesting that continuous measurement techniques, such as EC, could serve as an alternative in national N_2O inventories.

1. Introduction

Nitrous oxide (N_2O) is a powerful greenhouse gas (GHG) with a global warming potential ~300 times higher than carbon dioxide (CO_2) over a 100-year time horizon. Globally, agriculture contributes over 50% of anthropogenic N_2O emissions, i.e., 1.7–4.8 out of 2.8–8.9 Tg yr^{-1} (1 Tg = 1 million metric tonnes) to the atmosphere (Chapter 6, IPCC fifth report by Ciais et al., 2013). N_2O emissions from agricultural soils are mainly derived from nitrogen (N) inputs, such as urine deposition from grazing animals, N-fertiliser application and cultivation of N fixing plants (Reay et al., 2012). However, these N_2O emissions are not fully constrained because of the limitations in covering the temporal and spatial variations of N_2O fluxes using current measurement techniques, e.g., static chambers (Ciais et al., 2013; de Klein et al., 2006), that could over- or under-estimate N_2O emissions (Flechard et al., 2007, 2005). Improving observations in both space and time are desirable to quantify N_2O emissions and understand the interactions among regulators, e.g., substrate availability, soil temperature, soil moisture, oxygen supply (Dobbie and Smith, 2003; Liang et al., 2016, 2015; Shurpali et al., 2016; Yao et al., 2010), on N_2O emissions from agricultural soils. Improvements in measurement methods will also be beneficial for the development of mitigation strategies for N_2O emissions from agroecosystems.

To date, the static chamber method has been widely used to define N_2O emission factors (EFs) for specific management practices, climates and soils (de Klein and Harvey, 2012; Luo et al., 2013), and has been the main approach to produce official estimates of annual N_2O emissions for both national and global inventories. Chamber measurements

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https://doi.org/10.1016/j.agee.2018.09.010
Received 23 May 2018; Received in revised form 19 July 2018; Accepted 9 September 2018

provide particularly valuable information for comparisons between treatments by following a standardised measurement protocol (de Klein and Harvey, 2012). However, there are a number of limitations of this technique. For example, static chamber measurements are often conducted on soil surface areas far less than 1 m^2 and recorded once per day or less (de Klein and Harvey, 2012), which can lead to large uncertainties in extrapolated annual N_2O emissions at regional scales (Flechard et al., 2007; Levy et al., 2011). Enclosing of the soil surface with chambers may also change the N_2O concentration gradient between the soil and the sampled chamber headspace, resulting in an underestimation of N_2O fluxes (Rochette and Eriksen-Hamel, 2008). Many of these limitations are well known and attempts to minimise the effects of these shortcomings have resulted in standardised chamber design and sampling procedures (de Klein and Harvey, 2012; Rochette and Eriksen-Hamel, 2008).

An alternative approach for measuring N_2O fluxes across space and time is by using micrometeorological methods, including relaxed eddy accumulation (Desjardins et al., 2010; Nie et al., 1995), the flux gradient method (Laubach and Hunt, 2018, 2016), eddy covariance (EC) (Merbold et al., 2014) and the nocturnal boundary layer budget method (Pattey et al., 2006). The EC method is currently the most widely used micrometeorological method to measure CO_2 and CH_4 exchange between ecosystems and the atmosphere, and is now becoming more common for determining N_2O emissions from agricultural soils following the development of advanced laser spectroscopy (Cowan et al., 2016, 2014a; Huang et al., 2014; Merbold et al., 2014; Neftel et al., 2010; Shurpali et al., 2016), allowing integrated measurements at a finer temporal and much larger spatial scale than chamber methods. Until recently, the EC approach has required considerable maintenance. When using a tunable diode laser (TDL) (Molodovskaya et al., 2011; Scanlon and Kiely, 2003) or an early version of quantum cascade laser (QCL) (Kroon et al., 2007), considerations such as pre-drying air, frequent calibration, and requirement of a liquid nitrogen tank for cooling lasers, constrained their routine application in EC systems, especially at remote field sites. Recently, there has been development of instruments equipped with continuous-wave quantum cascade lasers (CW-QCL) that require less maintenance when coupled to an EC system (Cowan et al., 2015, 2014a; Imer et al., 2013). To date, there have been relatively few measurements of N_2O fluxes using EC systems equipped with a CW-QCL (Huang et al., 2014; Merbold et al., 2014; Neftel et al., 2010).

Being able to continuously measure N_2O fluxes at ecosystem scales, alongside key climate and management practices, may allow insights into factors that control N_2O fluxes through the underlying processes. The main pathways for controlling N_2O emissions from soils are microbial nitrification and denitrification. For autotrophic nitrification, ammonium (NH_4^+) and O_2 are the primary substrates, whereas, heterotrophic denitrification is mainly controlled by nitrate (NO_3^-) and organic carbon availability, and requires anaerobic conditions. Substrate availability is further controlled by other physical factors, e.g., soil temperature and moisture. The linkages between biotic and abiotic factors that control soil N_2O fluxes are complicated and still poorly understood (Butterbach-Bahl et al., 2013). Evidence from lab incubation experiments has indicated that the interactions between environmental factors and substrate availability associated with soil microbial activity could potentially affect the temporal and spatial patterns of N_2O emissions (Liang et al., 2016, 2015; Mooshammer et al., 2014; Rubol et al., 2013, 2012). Yet, information from integrated temporal-spatial measurements of N_2O fluxes at ecosystem scale is limited.

In grazed pastures, interactions between environmental factors and management practices that control N_2O fluxes are particularly complicated. Urine patches with high N loadings on small areas, averaging about 1000 kg N ha^{-1} per urination event for a dairy cow, is considered the dominant source of N_2O emissions in these pasture systems (Selbie et al., 2015). The spatial heterogeneity of urine patches, variations of soil temperature and moisture within a paddock, grazing intensity, plant species and their productivity, all result in high uncertainty in estimating N_2O fluxes using small-scale measurements. These complicated interactions between regulators in pastoral systems require continuous measurements at whole paddock scales to provide robust estimates for N_2O inventories. In New Zealand, N_2O is the third-largest component (10.5%) of its national GHG profile, and ~94% of these N_2O emissions are from agricultural soils (Ministry for the Environment, 2015). In particular, N_2O derived from N excreta as urine and dung deposited by grazing animals contribute up to 85% of the total N_2O emissions in grazed pastures (de Klein et al., 2010). Thus, quantifying N_2O fluxes and understanding their underlying controls is a research priority for assessing the trade-off between GHG emissions and a growing dairy industry.

At ecosystem scales, the interactions of soil moisture and temperature could affect N_2O fluxes in a different way compared to plot scales because of the high spatial heterogeneity of soil moisture and temperature. Numerous authors including Davidson et al. (1991) suggested a soil moisture optima of ~70% water-filled pore space (WFPS) for N_2O emissions (Davidson et al., 1991; Davidson and Verchot, 2000; Firestone and Davidson, 1989). The moisture response of N_2O fluxes has been widely tested through laboratory experiments or chamber measurements at small scales (Balaine et al., 2013; Flechard et al., 2007; Horváth et al., 2010; Van Lent et al., 2015), however, the corresponding responses at ecosystem scales have yet to be validated. In this study, we hypothesised that N_2O fluxes measured by EC would respond to the combined controls of soil temperature and moisture. We were particularly interested in evaluating the diurnal and seasonal pattern of N_2O fluxes and the underlying environmental controls in an intensive grazed pasture system, specifically following grazing events where there were large inputs of nitrogen with urine deposition. The results will improve our understanding of how N_2O flux patterns are controlled by environmental factors at ecosystem scales to allow for subsequent identification of management practices that have the potential to decrease N_2O emissions.

2. Methods

2.1. Site

This study was conducted on Troughton Farm, a commercial dairy farm located 3 km east of Waharoa in the Waikato region, North Island, New Zealand (37.78 °S, 175.80 °E, 54 m ASL). The mean annual temperature and precipitation between 1981 and 2010 were 13.3 °C and 1250 mm, respectively, according to records from a climate station 13 km to the south-west of the farm. The soils of the experimental area were a complex of three silt loams formed in rhyolitic and andesitic volcanic ash on rhyolitic alluvium (McLeod, 1992). The dominant soil was the Te Puninga silt loam (Mottled Orthic Allophanic soil) (Hewitt, 1998) with a clay content in the topsoil of approximately 20% (McLeod, 1992). The pasture sward of the experimental paddocks was dominated by perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), which was renewed in 2013, and the paddocks had been under long-term grazing for more than 30 years. We established an EC system to continuously monitor N_2O, CH_4 and H_2O fluxes, with associated soil and meteorological data (December 2016 to November 2017). The N_2O-EC system was co-located with a CO_2/H_2O EC system established in August 2012. The footprint of the EC tower was about 6 ha on average, covering three different paddocks with the dominant flux contribution from the paddock within which the EC system was located (for more details about the footprint and flux contributions refer to Rutledge et al. (2017a)).

2.2. Farm management

Troughton Farm (200 ha in total) consists of 67 paddocks ranging in size from 2.5 to 3.5 ha, each rotationally grazed by 2 to 3 herds of