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# Sheep urine patch $N_2O$ emissions are lower from extensively-managed than intensively-managed grasslands

Karina A. Marsden*, Jon A. Holmberg, Davey L. Jones, David R. Chadwick

*School of Environment, Natural Resources and Geography, Bangor University, Bangor, Gwynedd, LL57 2UW, UK*

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ABSTRACT

A large number of sheep graze extensively managed grasslands, including upland and hill areas. Excretal deposition of nitrogen (N) to upland soil is a potentially large source of the powerful greenhouse gas (GHG), nitrous oxide ($N_2O$), however, few studies have assessed urine-patch $N_2O$ emissions from upland areas. Current default excretal $N_2O$ emission factors (EFs) are based on intensively managed lowland systems, with cattle excreta as the N source. We hypothesised that $N_2O$ emissions could differ substantially from those of lowland systems, due to differences in soil type, climate, topography, pasture composition and management factors along altitudinal and productivity gradients. We investigated $N_2O$ emission factors across two seasons (spring and autumn), for an extensive semi-improved, temperate grassland using IPCC-compliant and representative sheep urine patches (in terms of urine chemical composition, urine patch size and N loading rates). An automated GHG monitoring system provided high-frequency GHG data from sheep urine patches (756 and 1112 kg N $ha^{-1}$ applied in spring and autumn, respectively), reference artificial sheep urine patches (1066 and 1004 kg N $ha^{-1}$ applied in spring and autumn, respectively) and control treatments. In spring, urine patch $N_2O$ emission factors were $-0.02 \pm 0.04$ (artificial sheep urine) and $0.03 \pm 0.09$% (real sheep urine) of the applied N; in autumn emission factors were $0.02 \pm 0.03$ (artificial sheep urine) and $0.08 \pm 0.04$% (real sheep urine) of the applied N. These values are much lower than default inventory values (1% of applied N) for excreta deposited by grazing livestock. There was a greater pasture foliar N content following urine application in spring as opposed to autumn, and a significantly longer residence time of extractable mineral N in autumn. Our findings demonstrate the importance of generating country-specific $N_2O$ EFs based on altitude/productivity gradients of livestock production, with implications for national inventories and the accuracy of sustainability metrics of lamb produced in the UK uplands.

## 1. Introduction

There are over 87 million sheep in the EU (Eurostat, 2017), many of which graze land classed as 'Less Favourable Areas' (LFA), under EC Directive 75/276. These areas support rural economies and the provision of ecosystem services, largely representing farms situated on mountainous terrain, under poor production conditions (e.g. acidic soils, sloping land, high rainfall, cool climate and short growing season). The large numbers of livestock grazing on hill land globally, has been identified as a potentially large source of the greenhouse gas (GHG), nitrous oxide ($N_2O$), via excretal deposition of nitrogen (N) to the soil (Luo et al., 2013). With a radiative forcing of ca. 296 times that of $CO_2$ and its contribution to the depletion of stratospheric ozone (Ravishankara et al., 2009), $N_2O$ is an important GHG associated with livestock production. Consumers of livestock products are becoming increasingly environmentally and ethically aware (Cantalapiedra-Hijar et al., 2016; Porqueddu et al., 2017), yet the environmental implications of contrasting livestock production systems (e.g. intensive vs. extensive grasslands) are not clearly differentiated in terms of their GHG emissions.

The default value of 1% of excretal N deposited by grazing sheep emitted as $N_2O$ (IPCC, 2006), has recently been lowered to a UK country-specific value of 0.44% (Brown et al., 2017) based on new data from nation-wide field experiments (Barneze et al., 2015; Chadwick et al., 2018; Misselbrook et al., 2014). Assuming a 60%–40% split in excretion of N to urine and faeces respectively (Webb and Misselbrook, 2004), the urine only emission factor is closer to 0.69% (Chadwick et al., 2018). Although the country-specific value is an improvement in accuracy upon the default value, it is still derived from cattle excreta derived from livestock fed on lowland pasture and applied to intensively managed lowland pastures. These figures, therefore, do not take account of the potential variation in emissions which could occur

* Corresponding author.
*E-mail address:* k.marsden@bangor.ac.uk (K.A. Marsden).

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due to differences in climate, soil, vegetation, topography and management factors (e.g. stocking density) along altitudinal and productivity gradients associated with hill grazing systems, nor does it apply specifically to sheep. The climate is generally cooler and wetter in the uplands, and inputs of N only occur via atmospheric deposition and livestock excreta. Extensively managed grassland soils are typically more acidic, contain greater amounts of organic matter compared to more intensively managed systems and have lower rates of mineralisation and nitrification (Williams et al., 1999).

Most studies which have measured $N_2O$ emissions from extensive grasslands have typically used synthetic sheep urine, or urine collected from lowland diets, presumably due to difficulties in collecting urine from sheep fed upland diets (e.g. Shand et al., 2002; Hoogendoorn et al., 2008). This does not take into account potential differences in the nitrogenous composition of sheep urine fed an upland diet, yet the composition of urine has been shown to alter N cycling and potential $N_2O$ emissions (Dijkstra et al., 2013; Luo et al., 2015). In addition, few studies use site-specific urine volumes and urine patch sizes, as reported in the meta-analysis of Selbie et al. (2015). Luo et al. (2013) found $N_2O$ emissions from sheep urine deposited to New Zealand hill land of low and medium slopes were lower than the current Intergovernmental Panel on Climate Change (IPCC) default value and suggested disaggregation of emissions based on slope class. Urine patch emission factors could also be disaggregated by grazing areas differing in primary productivity, yet limited data exist to underpin such an approach (Hopkins and Lobley, 2009).

In upland soils, low rates of nitrification following urea hydrolysis have been demonstrated following synthetic sheep urine addition (Thomas et al., 1988; Williams et al., 1999; Shand et al., 2002). Mahmood and Prosser (2006) reported a lag phase in nitrate production following synthetic sheep urine addition to upland soil microcosms. This was attributed to the structure of the initial ammonia oxidising microbial community in the extensively managed soil, with a lag phase being absent in intensively managed soils, due to a greater abundance of ammonia oxidisers (Webster et al., 2005). Reduced nitrification rates in upland soils could result in low $N_2O$ emissions from the urine patch, both from the process of nitrification itself and via reduced production of the substrate ($NO_3^-$) for denitrification.

Here, were provide IPCC-compliant year-round measurements of $N_2O$ fluxes (including high frequency data during the period with the highest likelihood of $N_2O$ loss) from sheep urine applied to a semi-improved, extensively grazed (upland) grassland, under two contrasting periods of the grazing season. To best reflect emissions from such areas, sheep urine representative in chemical composition, volume and patch size were used. We hypothesise that due to low rates of nitrification, emissions from these areas will be lower than the $N_2O$ EF of approximately 0.69% for urine-N applied in the lowlands (Chadwick et al., 2018), indicating that emissions from such areas are currently overestimated. Our data represent the first high frequency $N_2O$ data from sheep urine deposited to European hill grazing systems, which can contribute to national inventory $N_2O$ emission estimates, aid the development of more accurate sustainability metrics for upland lamb production (e.g. life cycle assessment and carbon footprint) and inform evidence-based policy decision making for the future of upland land management.

## 2. Materials and methods

### 2.1. Study site

The study took place on an enclosed, semi-improved, upland grassland at the Henfaes Research Station, Abergwyngregyn, North Wales (270 m a.s.l.; 53°13′N, 4°0′W; Fig. S1). The field (11.5 ha) has been managed under Welsh Government agri-environment schemes for 10 years (previously Tir Gofal and currently Glastir), with low input grazed pasture and mechanical bracken control options. The field is normally stocked at a density of approximately 4 ewes $ha^{-1}$ (ca. 0.32 Livestock Units $ha^{-1}$), and has not been fertilised, limed or re-seeded in over 30 years. The soil is classified as an Orthic Podzol (FAO, 1981; Fig. S2), with the pasture comprising a mosaic of British NVC classifications U4 (*Festuca ovina - Agrostris capillaris - Galium saxatile* grassland) and M56 (*Lolium perenne – Cynosurus cristatus* grassland) (Rodwell, 2000).

Two experimental areas were established, one to receive a composite spring urine application in June, 2016, and another to receive a composite autumn urine application in October, 2016, hereafter referred to as spring and autumn, respectively. Both sites were situated on a slope of 13% and livestock were removed from all plots at least 3 months prior to treatment application. Treatments consisted of i) control (no urine), ii) artificial sheep urine, and iii) real sheep urine ($n = 4$ for each treatment), laid out in a randomised block design. The vegetation in the plots were cut to a standard height (ca. 5 cm) 1 week prior to treatment application.

A meteorological station was installed at the experimental site (Skye Instruments Ltd., Llandrindod Wells, UK), recording weather data at half-hourly intervals. Missing data were gap-filled with meteorological data from the nearby COSMOS facility (Evans et al., 2016). The soil moisture probes ($n = 2$; 10HS Moisture Sensor, Decagon Devices Inc., WA, USA) were calibrated for volumetric water content according to manufacturer's instructions (Cobos and Chambers, 2010), as outlined in Starr and Paltineanu (2002), with field soil packed to field bulk density values (0.65 g $cm^{-3}$; mean of $n = 8$ measurements). Total pore space ($cm^3$ $cm^{-3}$) in the soil was calculated from the bulk density and the assumption of a particle density of 2.65 g $cm^{-3}$ for the mineral fraction and 1.4 g $cm^{-3}$ for the organic fraction (Rowell, 1994). Soil water-filled pore space (WFPS) was then calculated as a ratio of volumetric water content to soil porosity.

### 2.2. Soil characteristics

Soil characteristics ($n = 4$; 0–10 cm; Table 1) of both study areas (spring, sampled on 08/06/16 and autumn, sampled on 29/09/16) were determined. Bulk density (0–5 cm) was determined by inserting 100 $cm^3$ metal rings into the soil, and removing the intact core. Cores were oven-dried (105 °C) and sieved (< 2 mm) to remove and weigh stones, correcting soil bulk density values for stone weight and volume. Gravimetric soil moisture was determined by drying soil in an oven

**Table 1**
Characteristics of the Orthic Podzol ($n = 4$; 0–10 cm) used in spring (treatments applied on 14/06/16) and autumn (treatments applied on 04/10/16) field studies. Results are expressed on a dry soil weight basis, as means ± SEM, and letters denoting significant differences (two-sample t-test) between seasons of application.

| Orthic Podzol properties | Spring | Autumn |
|---|---|---|
| Bulk density (g $cm^{-3}$)[a] | 0.67 ± 0.03 | 0.64 ± 0.02 |
| Gravimetric moisture content (%) | 42.0 ± 3.4 a | 63.7 ± 0.8 b |
| Organic matter (%) | 16.9 ± 0.8 | 15.3 ± 0.6 |
| pH | 5.09 ± 0.08 | 4.98 ± 0.02 |
| EC (µS $cm^{-1}$) | 38 ± 6 a | 101 ± 7 b |
| Total C (g C $kg^{-1}$) | 81.2 ± 4.6 | 73.3 ± 7.0 |
| Total N (g N kg-1) | 6.1 ± 0.3 | 5.8 ± 0.5 |
| C:N ratio | 13.3 ± 0.2 | 12.6 ± 0.2 |
| N mineralisation rate (mg N $kg^{-1}$ $day^{-1}$) | 30.0 ± 2.2 | 29.1 ± 1.7 |
| Dissolved organic C (mg C $kg^{-1}$) | 352 ± 29.2 | 327 ± 9.84 |
| Total dissolved N (mg N $kg^{-1}$) | 64.7 ± 4.7 b | 51.5 ± 2.0 a |
| Microbial biomass C (g C $kg^{-1}$) | 2.61 ± 0.37 | 2.77 ± 0.08 |
| Microbial biomass N (mg N $kg^{-1}$) | 402 ± 45 | 409 ± 5 |
| Extractable $NO_3^-$ (mg N $kg^{-1}$) | 8.48 ± 1.31 | 5.27 ± 0.81 |
| Extractable $NH_4^+$ (mg N $kg^{-1}$) | 18.9 ± 0.2 b | 14.0 ± 1.0 a |
| Extractable P (mg P $kg^{-1}$) | 2.92 ± 1.43 | 0.97 ± 0.06 |
| Exchangeable Na (mg $kg^{-1}$) | 19.8 ± 2.6 a | 91.6 ± 12.3 b |
| Exchangeable K (mg $kg^{-1}$) | 14.9 ± 3.0 a | 39.4 ± 8.4 b |
| Exchangeable Ca (mg $kg^{-1}$) | 231 ± 42 | 328 ± 86 |

[a] 0–5 cm.