Nutr Cycl Agroecosyst
DOI 10.1007/s10705-015-9685-6

ORIGINAL ARTICLE

# Nitrous oxide emissions from cool-season pastures under managed grazing

**Randall D. Jackson · Lawrence G. Oates · Walter H. Schacht · Terry J. Klopfenstein · Daniel J. Undersander · Matthew A. Greenquist · Michael M. Bell · Claudio Gratton**

Received: 26 November 2014 / Accepted: 17 February 2015

**Abstract** High stocking densities on grazed pastures may promote nitrous oxide ($N_2O$) loss from soil to the atmosphere. However, studies of $N_2O$ fluxes in cool-season pastures of North America are lacking. We performed two experiments in which measured $N_2O$ fluxes were bootstrapped with re-sampling ($n = 100$, with 10,000 iterations), which allowed us to generate an empirical distribution of mean fluxes to understand how pasture management strategies might affect $N_2O$ emissions. In Experiment 1, $N_2O$ fluxes were estimated in southern Wisconsin pastures under rotational grazing, continuous grazing, haymaking, and no agronomic production. Nitrous oxide fluxes were significantly positive under rotational grazing at our research farm [21.6 (se = 10.3) $\mu g\ m^{-2}\ h^{-1}$], but not significantly different than zero under the other three treatments or rotationally grazed paddocks across eight working farms. In Experiment 2, we measured $N_2O$ fluxes in eastern Nebraska before, during, and after two rotational grazing events under two N-input treatments—inorganic N fertilizer and supplemented dried distillers grains—and an unfertilized control. Nitrous oxide fluxes were positive (20–100 $\mu g\ m^{-2}\ h^{-1}$) in periods following rain, but otherwise not significantly different than zero. Post-grazing, $N_2O$ emissions were lower from the control than fertilized or supplemented treatments. These experiments show cool-season pastures can be a source of $N_2O$ to the atmosphere, but primarily following grazing events that coincide with significant precipitation. However, even though on-farm paddocks are in varying states of recovery from defoliation, farm scale emissions, although episodic, are likely to be positive in years with above average precipitation.

**Keywords** Grazed pastures · Greenhouse gases · Temperate grassland

---

R. D. Jackson · D. J. Undersander
Department of Agronomy, University of Wisconsin-Madison, 1575 Linden Drive, Madison, WI 53706, USA

L. G. Oates (✉)
Nelson Institute for Environmental Studies, University of Wisconsin-Madison, 1575 Linden Drive, Madison, WI 53706, USA
e-mail: oates@wisc.edu

W. H. Schacht · M. A. Greenquist
Department of Animal Science, University of Nebraska-Lincoln, Lincoln, NE 68583, USA

T. J. Klopfenstein
Cargill Animal Nutrition, Lincoln, NE 68516, USA

M. M. Bell
Department of Community and Environmental Sociology, University of Wisconsin-Madison, 1450 Linden Drive, Madison, WI 53706, USA

C. Gratton
Entomology Department, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, USA

## Abbreviations

| | |
|---|---|
| ARDC | University of Nebraska-Lincoln Agricultural Research and Development Center |
| AU | Animal units |
| CONT | Continuous grazing |
| DDGS | Corn-based dried distillers grains with solubles |
| FERT | Inorganic N fertilizer |
| HARV | Harvest |
| MIRG | Management-intensive rotational grazing |
| NOFERT | Unfertilized control |
| NONE | No agronomic management |
| SUPP | Supplemented dried distillers grains |
| UIP | Undegradeble intake protein |

## Introduction

The atmospheric concentration of nitrous oxide ($N_2O$) has rapidly increased since the Industrial Revolution concomitant with agricultural intensification (IPCC 2001), and more recently (1990–2012) global $N_2O$ emissions from agriculture have increased 9 % (IPCC 2013). Many have pointed to managed grasslands as a land use that may mitigate increasing greenhouse gases in the atmosphere because of their potential to sequester C (Allard et al. 2007; Conant and Paustian 2002; Conant et al. 2001; Follett et al. 2001). However, $N_2O$ losses from pastures may offset their ability to buffer global climate change (Conant et al. 2005; Flechard et al. 2005; Oenema et al. 2005). Alternatively, grasslands may be a sink for $N_2O$ under very low redox potential (for a review see Chapuis-Lardy et al. 2007).

Grazing on pastures is known to promote N losses in Europe and Oceania (Ruzjerez et al. 1994; Williams et al. 1998) and reports from New Zealand and Australia show that grazing management can significantly modify C and N greenhouse gas fluxes to the atmosphere (Luo et al. 2000; Ross et al. 1995; Ruzjerez et al. 1994), however, similar studies of cool-season grass-dominated pastures of North America are lacking. The type, intensity, and frequency of defoliation are likely to influence gaseous N loss by affecting the quantity and quality of plant biomass, soil solution nitrate, water-filled soil pore space, and soil temperature (Livesley et al. 2008; Uchida et al. 2008).

In general, pasture application of inorganic N occurs as ammonium nitrate or ammonium sulfate and is spread in a relatively uniform manner with mechanical devices. Typical recommendations for N subsidy to temperate pastures are 50–100 kg $ha^{-1}$ $y^{-1}$ of N split into spring and fall applications. The amount of N applied as fertilizer to cool-season grasses is often in excess of plant uptake (Mosier 2001) and the apparent N recovery rate can be as little as 17–50 %. Nitrogen use efficiency can be improved by increasing N retention, targeting N application to better coincide with plant demand, and/or reducing N inputs (De Vries and Bardgett 2012). In growing animals, retention of N can be increased by improving body weight (BW) gain through supplementing energy and undegradable intake protein (UIP) to forage-based ruminant diets (Greenquist et al. 2011; Klopfenstein et al. 2001; Lake et al. 1974). Corn-based dried distillers grains with solubles (DDGS) are a good source of both energy and UIP and improve average daily gain of beef cattle grazing forages (Greenquist et al. 2009; Loy et al. 2007). Supplementing cattle on pasture with DDGS also effectively acts as N fertilization because DDGS is high in N (5 % DM) and excess N is excreted in the urine. Supplementing cattle on pasture at 2–3 kg $head^{-1}$ $d^{-1}$ can result in a N fertilization rate of 35–40 kg $ha^{-1}$ (see Greenquist et al. 2011). Nitrogen inputs from excreta and the subsequent effects on N losses to the atmosphere are extremely patchy at scales from centimeters (Koops et al. 1997) to hundreds of meters (Jackson et al. 2007). This spatial heterogeneity makes it very difficult to accurately quantify N losses to the atmosphere (Groffman et al. 2006).

Livestock grazing of pastures is a growing phenomenon in the Midwest and eastern Great Plains of the United States. Jackson-Smith et al. (1996) estimated that about 7 % of all dairy farms in Wisconsin maintained some form of grazing as a management strategy in 1993. An update to this study indicated this estimate had grown to 26 % by 2005 (Brock and Barham 2009). A particular form of grazing, management-intensive rotational grazing (MIRG), which entails livestock grazing in relatively small paddocks at high densities [50–150 animal units (AU) $ha^{-1}$], but for short durations (1–3 days), has been touted as beneficial to both graziers and grazers

(Paine et al. 2000). However, many of those claiming to use MIRG actually graze in ways that are similar to continuous or extensive grazing (Ostrom and Jackson-Smith 2000), where animals are moved infrequently.

Using two university owned research properties with pasture infrastructure and ongoing pasture research, as well as eight privately owned grass based farms, we explored two questions relevant to management of temperate grasslands dominated by cool-season grasses: (1) Are $N_2O$ fluxes from these grasslands positive, negative, or neutral? and (2) Does management of these pastures affect the size and direction of these fluxes? Our approach was to assess patterns at a management-relevant scale. We did this with two experiments, one assessing harvest management effects and the other examining combinations of time-since-grazing and N inputs.

## Methods

### Experiment 1—harvest management effects on $N_2O$ fluxes

In August 2004 we implemented a randomized complete block design with three blocks and four treatments: MIRG, CONT, HARV, and NONE (management-intensive rotational grazing, continuous grazing, harvesting grass for hay, and ungrazed/fallow land, respectively) at the Franbrook Farm, a University of Wisconsin (UW) research property located 25 km south of Madison, WI, USA (42°44′17″N, 89°45′13″W and 265–320 m asl). Annual precipitation averaged 930 mm, of which 100 mm is from snow, from 1971 through 2000. During the same period, the average minimum (January) temperature was −7 °C and the maximum (July) was 22 °C. The plots on which we worked were historically cropped annually in a tilled maize-soybean rotation, but intermittently grazed perennial pasture was established in 1998 and remained in place through this study period (2004–2005).

Soils of Franbrook are ~90 cm deep and are classified as Otter silt loam (Cumulic Endoaquolls), Arenzville silt loam (Typic Udifluvents), and Huntville silt loam (Cumulic Hapludolls) which are mesic, fine-silty, mixed, superactive soils derived from sandstone and limestone parent material. Herbaceous vegetation on this site was dominated by C3 grasses [*Poa pratensis* L. (Kentucky bluegrass), *Phleum pratense* L. (timothy), *Dactylis glomerata* L. (orchard grass), *Bromus inermis* Leyss. (smooth bromegrass)] and clovers [*Trifolium pratense* L. (red clover) and *T. repens* L. (white clover)]. In a subsequent study, aboveground net primary productivity on the grazed portion of this site ranged from 600 to 1200 g dry biomass $m^{-2}$ $y^{-1}$ (Oates et al. 2011). Total precipitation was slightly higher than normal in 2004 (1015 mm) and much lower in 2005 (645 m or 69 % of 30-year average). In August 2005, we collected and composited six soil subsamples from each experimental unit to determine soil texture (particle size density analysis, Robertson 1999) and total soil C and N (Flash EA1112, CE Elantech, Lakewood, New Jersey, USA) (Table 1).

Beginning in August 2004, continuously grazed paddocks (8.1 ha in each block) were grazed by separate herds of ~25 cow-calf pairs (1 pair = 1.3 AU) for 28–30 days $month^{-1}$ (i.e., a stocking density of ~112–120 AU days $month^{-1}$). MIRG paddocks (0.6 ha) were grazed at high stocking densities for 1–2 days (i.e., a stocking density of 54–128 AU days $month^{-1}$) and then allowed to rest for the remainder of the month. Monthly grazing cycles began in August and continued through October 2004 (three grazing cycles), were stopped during winter, and resumed in late May through October 2005 (five grazing cycles). To simulate the harvesting of hay (HARV), aboveground biomass was mechanically clipped and removed from 0.3-ha paddocks in early July and late August 2005. Finally, we set aside 0.3-ha paddocks as controls and no agronomic management was applied (NONE).

No fertilizer was applied to any of the treatment paddocks in 2003 or 2004. In September 2005,

**Table 1** Soil texture, total carbon, and total nitrogen [mean (±SE), n = 3 per treatment] from 6 composited soil cores taken from the surface 10-cm in each experimental unit

| Parameter | MIRG | CONT | HARV | NONE |
|---|---|---|---|---|
| Soil texture | | | | |
| % Sand | 32 (6) | 29 (5) | 23 (7) | 20 (6) |
| % Silt | 54 (5) | 57 (1) | 64 (6) | 69 (4) |
| % Clay | 14 (7) | 14 (5) | 13 (3) | 11 (2) |
| Total soil C | 4.1 (0.3) | 3.7 (0.03) | 4.6 (0.8) | 4.3 (0.4) |
| Total soil N | 0.3 (0.04) | 0.3 (0.01) | 0.4 (0.1) | 0.3 (0.1) |

granular ammonium phosphate (11-44-0) fertilizer was broadcast applied to the surface at the rate of 57 kg $ha^{-1}$ of N to all treatment areas except NONE.

In addition to the Franbrook Farm experiment, we collected $N_2O$ from eight grass-based farms that were known to be practicing MIRG and were located within 50 km of Madison, Wisconsin, USA (Table 2). With the assistance of the owners at each farm, we located MIRG paddocks that had been recently grazed by either dairy cows (three farms), beef cattle (three farms), or sheep (two farms). Farmers varied the amount of time animals were in the MIRG paddocks and sometimes mowed paddocks after animals had exited in order to stimulate plant production.

### Experiment 2—fertilizer, supplementation and time-since-grazing effects on $N_2O$ fluxes

The experiment was conducted at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center (ARDC) near Mead, NE (41°8′48″N, 96°29′52″W and 315 m asl). The area is characterized by a continental climate with an average maximum temperature of 30.9 °C in July and an average minimum temperature of −12 °C in January. The 10-year average annual precipitation for this area was 693 mm,[1] of which 75 % falls in the form of rain from April through September. The soil type is a Pohocco silty clay loam (Typic Eutrudept) which is a fine-silty, mixed, superactive, mesic soil derived in Peorian loess. The study site consisted of three pastures of smooth bromegrass which over the previous 10 years were fertilized annually with approximately 90 kg $ha^{-1}$ of N and grazed heavily in May and October by calves and yearlings.

Crossbred (predominately Angus) steers (330 ± 10 kg) were used in a randomized complete block design with three blocks and three treatments. The treatments were (1) paddocks fertilized with 90 kg $ha^{-1}$ of N in the form of surface applied Urea in early April and initially stocked with yearling steers at 9.2 animal unit months (AUM) $ha^{-1}$ (FERT) (2) non-fertilized paddocks initially stocked at 6.4 AUM $ha^{-1}$ (NOFERT), and (3) non-fertilized paddocks stocked at the same rate as the FERT with 2.3 kg DM of corn DDGS supplemented daily per steer for the entire treatment period (SUPP). This amount of supplementation (0.58 % of average BW daily) was slightly greater than that used by Morris et al. (2005, 2006), who reported improved animal performance while maintaining complete consumption of the DDGS supplement at amounts of 0.50 % of BW daily. The stocking rate for the fertilized treatment was based on longer-term stocking rate records for the site and UNL extension recommendations (Rehm et al. 1971; Waller 1986). For the non-fertilized treatment, previous research on pastures adjacent to the experimental pastures indicated a 30 % decrease in available forage on non-fertilized compared with N fertilized (90 kg $ha^{-1}$) smooth bromegrass (Schlueter 2004).

Within each of the three blocks, treatments were originally assigned randomly to one of three paddocks in 2005. Treatment allocation to the individual paddocks was the same for the July 2007 and May 2008 sampling period. Paddocks were 2.0 ha for FERT and SUPP, and 2.9 ha for NOFERT and were grazed from late April through September. Each paddock was further divided equally into 6 strips to implement management-intensive grazing. The cattle were rotated through all six strips in each of five grazing cycles. The period of stay was 4 days per strip in cycle 1 and 6 days per strip in cycles 2, 3, and 4. Period of stay in cycle 5 varied from 4 to 6 days based on available forage mass.

We used 45 crossbred steers (330 ± 10 kg) that were blocked by weight and randomly assigned to the nine paddocks. We used five steers per paddock as tester animals. To maintain comparable grazing pressure among treatments and year we used a variable stocking rate, which was achieved by adding and subtracting cattle in a put-and-take system. The number of animals was managed by estimating forage mass and visual observations of available forage.

### Nitrous oxide measurements

At the Franbrook Farm in Wisconsin, we measured pre-treatment $N_2O$ fluxes from all plots in July 2003 and March 2004. Starting in September 2004 and continuing through October 2005, $N_2O$ was measured the day following each monthly MIRG grazing event. Measurements at the Wisconsin satellite farms occurred within 1 week after the MIRG event for three periods during the 2005 growing season. At ARDC in Nebraska, we measured $N_2O$ for two periods

---

[1] NCDC, National Climatic Data Center for Mead, NE http://cdo.ncdc.noaa.gov/ancsum/ACS.

**Table 2** Farm type, farm location, soil type and class, and pasture management applied for eight grass-based farms within 50 km of Madison, WI

| Farm | Grazing animal | County | Major soil type(s) | Soil class | Pasture percent[1] | Pasture management | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | MIRG | CONT | HARV | NONE |
| 1 | Beef cattle | Iowa | NewGlarus silt loam | Fine-silty over clayey, mixed, superactive, mesic Typic Hapludalfs | 65 | × | × | × | × |
| | | | Dubuque silt loam | Fine-silty, mixed, superactive, mesic Typic Hapludalfs | 27 | | | | |
| 2 | Beef cattle | Columbia | Ossian silt loam | Fine-silty, mixed, superactive, mesic Typic Endoaquolls | 34 | × | × | × | × |
| | | | St. Charles silt loam | Fine-silty, mixed, superactive, mesic Typic Hapludalfs | 21 | | | | |
| | | | Lapeer fine sandy loam | Coarse-loamy, mixed, semiactive, mesic Typic Hapludalfs | 18 | | | | |
| 3 | Beef cattle | Columbia | Plano silt loam | Fine-silty, mixed, superactive, mesic Typic Argiudolls | 70 | × | × | × | × |
| 4 | Dairy cows | Dane | Plano silt loam | Fine-silty, mixed, superactive, mesic Typic Argiudolls | 41 | × | × | × | × |
| | | | McHenry silt loam | Fine-loamy, mixed, superactive, mesic Typic Hapludalfs | 24 | | | | |
| | | | Ringwood silt loam | Fine-loamy, mixed, superactive, mesic Typic Argiudolls | 23 | | | | |
| 5 | Dairy cows | Columbia | Griswold silt loam | Fine-loamy, mixed, superactive, mesic Typic Argiudolls | 45 | × | × | × | × |
| | | | Sisson fine sandy loam | Fine-loamy, mixed, semiactive, mesic Typic Hapludalfs | 19 | | | | |
| 6 | Dairy cows | Columbia | Lomira silt loam | Fine-silty, mixed, superactive, mesic Typic Hapludalfs | 54 | × | × | × | |
| | | | Elburn silt loam | Fine-silty, mixed, superactive, mesic Aquic Argiudolls | 14 | | | | |
| 7 | Sheep | Dane | Batavia silt loam | Fine-silty, mixed, superactive, mesic Mollic Hapludalfs | 54 | × | × | | × |
| | | | Dresden silt loam | Fine-loamy, sandy/sandy-skeletal, mixed, active, mesic Mollic Hapludalfs | 27 | | | | |
| 8 | Sheep | Iowa | Dubuque silt loam | Fine-silty, mixed, superactive, mesic Typic Hapludalfs | 69 | × | | × | × |
| | | | NewGlarus silt loam | Fine-silty over clayey, mixed, superactive, mesic Typic Hapludalfs | 29 | | | | |

[1] Percent pasture reflects the major soil type encountered and may not add up to 100 %

**Table 3** Environmental factor means (SE) at Franbrook Farm (WI) and the Agricultural Research and Development Center (NE)

| Year | Site | Treatment | Soil temp (°C) | Volumetric water content (%) | $NH_4+$ (ug N/gdw) | $NO_3-$ (ug N/gdw) |
|---|---|---|---|---|---|---|
| 2004 | Franbrook | MIRG | | 37.9 (0.4) | 3.96 (0.86) | 0.64 (0.24) |
| | | CONT | | 35.7 (0.2) | 5.46 (1.31) | 0.76 (0.19) |
| | | HARV | | 34.8 (0.5) | 3.43 (1.39) | 1.05 (0.32) |
| | | NONE | | 34.0 (0.4) | 4.27 (0.71) | 0.57 (0.13) |
| 2005 | Franbrook | MIRG | 14.0 (3.0) | 25.2 (1.0) | 2.44 (0.79) | 1.29 (0.62) |
| | | CONT | 14.2 (3.0) | 23.6 (1.1) | 2.28 (0.89) | 1.74 (0.94) |
| | | HARV | 13.2 (2.6) | 27.5 (0.1) | 3.02 (1.37) | 1.17 (0.52) |
| | | NONE | 12.5 (2.6) | 27.9 (0.1) | 3.13 (1.10) | 1.48 (0.67) |
| 2007 | ARDC | NOFERT | 24.3 (1.6) | 17.5 (2.9) | | |
| | | FERT | 24.3 (1.7) | 17.0 (3.0) | | |
| | | SUPP | 24.2 (1.8) | 18.6 (3.2) | | |
| 2008 | ARDC | NOFERT | 16.9 (1.9) | 26.0 (5.0) | 6.14 (1.25) | 6.73 (1.68) |
| | | FERT | 16.4 (2.0) | 24.6 (4.6) | 8.56 (3.13) | 10.7 (8.79) |

(22 June–16 July 2007 and 17 May–20 June 2008) from all treatment plots 1 day before, 3 days into, and five times over a period of about 20 days after each 4-day grazing event.

We used vented, static chambers at all sites to capture $N_2O$ fluxes between the soil and the atmosphere (Livingston and Hutchinson 1994). In each experimental unit we installed eight circular 25-cm diameter × 15-cm deep PVC collars 5-cm into the ground (Hutchinson and Livingston 2002). Vegetation was then hand-clipped to 5-cm stubble height. To avoid disturbance of the sample area, we minimized trampling during collar installation and waited a minimum of 30 min to first sampling to allow soil-atmosphere equilibration. Collars were removed during grazing events but remained in the ground until a series of post-grazing measurements were completed. All measurements were made between 1100 and 1600 h local time.

To initiate gas extraction, a 25-cm diameter × 20-cm deep PVC chamber was fitted over an installed collar. These chambers had 2-mm diameter vents and a septum for syringe insertion. Once the chamber was in place, extractions of headspace gas were made over a 30 min period using a 30-ml nylon syringe and a 23-gauge needle. Gas samples were transferred from the syringe into 30-ml glass vials fitted with 2-cm rubber septa. We also collected ambient air and known gas standards (10 ppm $N_2O$) to assess the potential for storage degradation between sampling and gas analysis. Vials were returned to UW-Madison where they were analyzed for $N_2O$ with an electron capture detector (Shimadzu GC-14B, Shimadzu Analytical and Measuring Instruments Division, Kyoto, Japan). For treatment comparisons, constant and linear fluxes were assumed (Holland et al. 1999; Duran and Kucharik 2013) and hourly fluxes were calculated by doubling the calculated 30-min flux. To show relative comparisons of known environmental factors affecting $N_2O$ emissions, soil temperature and volumetric water content were measured, and inorganic soil nitrogen concentrations were assayed, at several times during the measurement period (Table 3).

## Data analysis

Estimation of trace gas fluxes is difficult because of tremendous spatial variability across many scales (Velthof et al. 1996a). Further complicating the issue, the temporal distribution of $N_2O$ fluxes usually follow what might be characterized as a log normal distribution (Velthof et al. 1996b)—with many values near zero and a very few large fluxes. However, the occurrence of negative fluxes (i.e., atmospheric $N_2O$ entering soils) makes the usual log transformation of such a dataset for parametric statistical analyses inappropriate. Therefore, we made bootstrap estimates of hourly $N_2O$ fluxes from all treatments and sampling times at all sites. For each treatment within a given dataset (i.e., Franbrook, ARDC, or on-farm datasets), fluxes were re-sampled ($n = 100$, with 10,000 iterations) across blocks to generate an empirical distribution of mean fluxes. A treatment was considered to have significant fluxes if the envelope containing 95 % of the bootstrapped means (i.e., the interval <97.5 and >2.5 % of the empirical distribution) did not contain zero (Crawley 2002). While other approaches to calculating 95 % confidence intervals around bootstrapped means exist (e.g., bias-corrected intervals), our empirical distributions were quite symmetrical and none of our results were marginal with respect to whether the distribution was different than zero.

## Results

### Experiment 1

Nitrous oxide fluxes were significantly positive from MIRG treatment paddocks at the Franbrook Farm in 2005 (Fig. 1). The bootstrapped mean $N_2O$-N flux was 21.6 μg $m^{-2}$ $h^{-1}$. Across eight southern Wisconsin farms, $N_2O$ fluxes from MIRG paddocks were not significantly different from zero and variability was similar to the variability within the MIRG treatments at the Franbrook Farm (Fig. 1). Fluxes of $N_2O$ were not significantly different from zero for the three other pasture management treatments at Franbrook, but variability in the NONE treatment was lower than for CONT and HARV (Fig. 1). Pre-treatment (Jul. 2003 and Mar. 2004) $N_2O$ fluxes were positive (Fig. 2). Once MIRG treatments commenced (Aug. 2004), $N_2O$ fluxes were strongly positive (Sep. and Nov. 2004) whereas the other treatments were weakly negative. This pattern disappeared for much of the 2005 season, but was again evident in Oct. 2005 (Fig. 2).

### Experiment 2

The 2007 sampling period at ARDC was very dry while significant rain occurred during the post-grazing period of 2008 (Fig. 3). In 2007, two combinations of time and treatment were significant—SUPP 1 day prior to grazing was negative and FERT was positive 19 days post-grazing. The initial two time points were relatively dry in 2008, so the size of $N_2O$ flux was similar to 2007, but precipitation coincided with the post-grazing sampling. During this period, $N_2O$ fluxes were always positive with means in the range of 20–100 μg $m^{-2}$ $h^{-1}$. The only separation of treatments occurred in the last two time points when NOFERT paddocks appeared to be emitting less than FERT and SUPP.

## Discussion

In the 2nd year of our disturbance experiment (Experiment 1), MIRG promoted $N_2O$ emissions to

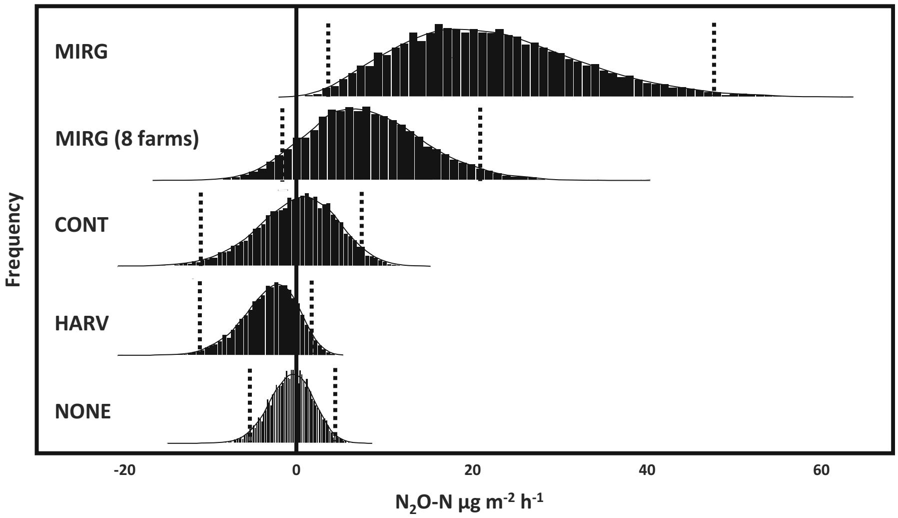


**Fig. 1** Bootstrapped distribution of mean $N_2O$ fluxes in 2005 from four pasture management treatments at the Franbrook farm (MIRG, Management-intensive Rotational Grazing; CONT, Continuous grazing; HARV, Harvested for hay; NONE, no agronomic management) and MIRG paddocks across eight grass-based farms in southern Wisconsin. Means were calculated for 100 resamples in 10,000 iterations. *Dotted lines* bracket 95 % of calculated means from the empirical distributions

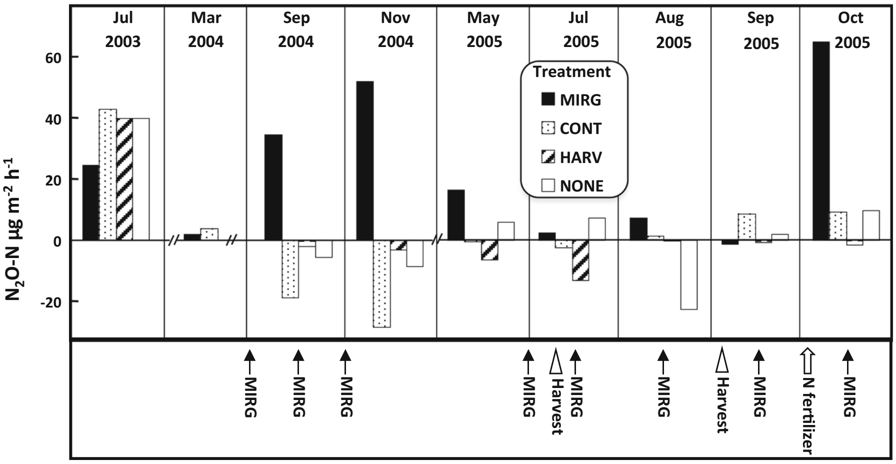
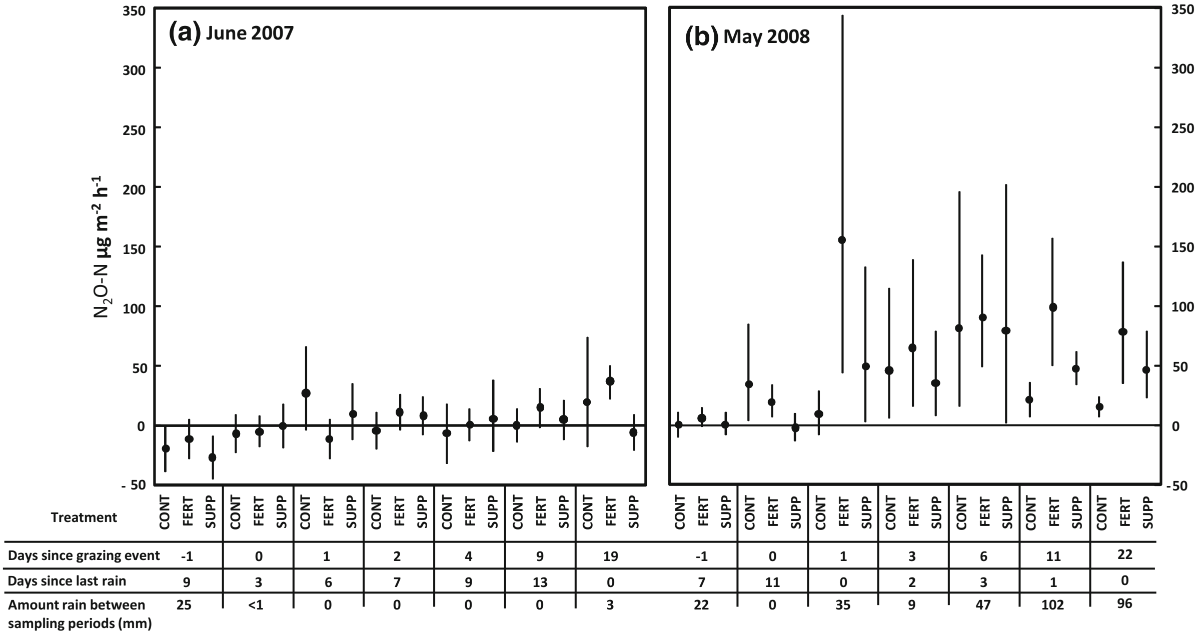


**Fig. 2** Mean $N_2O$ fluxes for each treatment across three blocks at Franbrook farm for selected time points during the 2003 through 2005 growing seasons. *Open arrow* indicates relative timing of nitrogen fertilizer applications (MIRG, CONT and HARV only), *closed arrows* indicate MIRG grazing events, and *open triangles* indicate HARV events



| Treatment | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP | CONT<br>FERT<br>SUPP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Days since grazing event | -1 | 0 | 1 | 2 | 4 | 9 | 19 | -1 | 0 | 1 | 3 | 6 | 11 | 22 |
| Days since last rain | 9 | 3 | 6 | 7 | 9 | 13 | 0 | 7 | 11 | 0 | 2 | 3 | 1 | 0 |
| Amount rain between sampling periods (mm) | 25 | <1 | 0 | 0 | 0 | 0 | 3 | 22 | 0 | 35 | 9 | 47 | 102 | 96 |

**Fig. 3** Bootstrapped distribution of mean $N_2O$ fluxes from three pasture management treatments (CONT, Control; FERT, inorganic N fertilizer; SUPP, dried distillers grain suppement) at the Mead Research Station in **a** June 2007 and **b** May 2008. *Upper* and *lower bars* contain 95 % of the means calculated for 100 resamples in 10,000 iterations. Below the fertility treatments on the x-axis are number of days since a MIRG grazing event, the number of days since last rain, and the amount of rain between gas sampling periods

the atmosphere while fluxes from two other harvest treatments and our control were not significantly different from zero. Since the three disturbance treatments all received the same fertilizer inputs, these results lead us to believe that grazing management has a stimulatory effect on $N_2O$ emissions. This probably stems from greater nitrification and denitrification as a result of higher inorganic N availability and/or moisture in the soil, which arises from a combination of (1) intense defoliation resulting in less short-term plant uptake of N and water (Hamilton et al. 2008; Houlbrooke and Laurenson 2013), (2) inputs of N as urine (Cameron et al. 2013), and (3) compaction and pugging of the soil from animals (Houlbrooke et al.

2011). We did not collect data to separate these mechanisms.

Fluxes from MIRG paddocks on the eight working farms were not significantly different from zero. It is important to note that the $N_2O$ emissions we observed in MIRG plots at the Franbrook Farm always were measured 1 day following MIRG grazing events. Differences in sample timing between Franbrook and the eight farms leads us to suspect rapid decline of $N_2O$ emissions post-grazing such that positive emissions were observed only when we sampled the day following grazing or that the N inputs on these farms was not sufficient to result in $N_2O$ emissions. Information about time-since-grazing and fertilizer application on the eight farms was qualitative and narrative in form, but generally we measured plots that had been "recently grazed" in an effort to replicate our procedure at the Franbrook Farm. All farmers indicated some degree of N fertilizer was applied to their pastures in the past, but their anecdotal information about the timing and amount applied was vague and very general. Stubble heights at the time of sampling in these paddocks were similar to what we observed at Franbrook post-grazing (5–15 cm, data not shown), but several days may have elapsed since grazing in many cases. This spurred our effort to quantify fluxes before, during, and for a period after grazing events (i.e., Experiment 2).

Results from Experiment 2 demonstrate the paramount importance of moisture for $N_2O$ loss from soil to the atmosphere. When fluxes were high, they lasted longer for paddocks receiving exogenous N. That said, similar to pretreatment Franbrook pastures in 2003, significant $N_2O$ emissions were observed from unfertilized but grazed control paddocks at ARDC. These observations all point to MIRG paddocks being sources of $N_2O$ to the atmosphere during wet periods of the growing season, with these contributions being stimulated by exogenous N.

Van Groenigen et al. (2005) showed that $N_2O$ pulses from soils with controlled rates of applied urine did not peak until ~10 days post-treatment, which contradicts our interpretation of a rapid (~1 day) transformation of urine N–$N_2O$. However, this work occurred on sandy soils with combinations of dung, urine, and compaction applied by the researchers. Our silt loams at Franbrook and silty clay loams at ARDC likely have lower percolation rates, which may have allowed more rapid microbial transformation of urine N near the soil surface. Flechard et al. (2005) found that haying resulted in a spike of $N_2O$ emissions that waned exponentially in the days that followed the harvest, so the pulse of emissions we observed immediately following grazing may have been related to defoliation itself rather than N inputs via excreta. However, we did not observe emission spikes following HARV treatments on our Franbrook site, so this may be related more to fertilizer regimes on hay fields as in Flechard et al. (2005) and Hyde et al. (2006).

Our MIRG $N_2O$ emissions of 20–100 $\mu g\ m^{-2}\ h^{-1}$ were reasonably similar to estimates from other studies of temperate grasslands. In grass-clover mixtures in the Czech Republic, Šimek et al. (2004) estimated $N_2O$ emissions of 15 $\mu g\ m^{-2}\ h^{-1}$ on fields being fertilized and harvested for hay. Flechard et al. (2005) compared intensively managed and grazed to extensively grazed grasslands in Central Switzerland and found median $N_2O$ emissions of 144 and 72 $\mu g\ m^{-2}\ h^{-1}$, respectively. Mosier et al. (2002) reported $N_2O$ emissions of 1.7 $\mu g\ m^{-2}\ h^{-1}$ for Colorado shortgrass steppe—a much drier system.

MIRG paddocks are in various states of vegetative recovery from grazing at all times, so $N_2O$ fluxes are likely systematically different throughout a farm from paddock-to-paddock, covarying negatively with time-since-grazing. Therefore, a standardized comparison of grazing systems at the whole-farm level would assume that a small fraction of all MIRG paddocks are emitting $N_2O$ on a given day. However, during periods following rain, emissions will likely be positive and may last longer in paddocks receiving N inputs. The size and variability of fluxes at the whole-farm level rendered fluxes not different from zero for the CONT, HARV, and NONE treatments in our manipulative study and MIRG paddocks on the working farms we sampled, but these MIRG fluxes were most likely moderated by the lag time in sampling after the grazing event. Sampling 1 day post-grazing on the MIRG pastures of manipulative Experiment 1, and on a series of days post-grazing in Experiment 2, indicate MIRG pastures are a source of $N_2O$ to the atmosphere, especially when fertilization and grazing events coincide with precipitation. Also, while a farm under CONT grazing management with no fertilizer applied is likely supporting relatively low levels of $N_2O$ fluxes at the grazing system level, concentration of livestock and their excreta in "camping areas" around gates, shade, and water sources may promote significant $N_2O$

emissions (Anger et al. 2003; Hynst et al. 2007; Koops et al. 1997), but this hypothesis deserves further study.

## Conclusions

We found pasture systems under management-intensive rotational grazing were a source of $N_2O$ to the atmosphere during periods immediately following grazing and preciptation events, while other management systems—continuously grazed, harvested for hay, and ungrazed treatments—did not have significant $N_2O$ emissions. While all pastures exhibited emission spikes following precipitation, pastures receiving exogenous N took longer to return to background emission levels. Inferences from these results should be limited to the 1–3 days immediately following intensive grazing of a paddock. Moreover, while our study included both research and working farm pastures, the range of grazing management referred to as MIRG by farmers make generalizations tenuous.

**Acknowledgments** Thanks to Jon Bleier, John Albright, Jesse Rucker, Trish Oates, Liz Froelich, Kelly Brink, Jon Soper, Neal Bryan, and Andrea Watson for field and lab assistance. Graduate student support came from a UW College of Agriculture and Life Sciences Interdisciplinary Hatch Grant and Multi-State Project NC-1021 Nitrogen Cycling, Loading, and Use Efficiency in Forage-Based Livestock Production Systems, while supplies and expenses were supplied by grants from the UW Center for Integrated Agricultural Systems, the Grazing Lands Conservation Initiative, and the Nebraska Corn Board.

## References

Allard V, Soussana JF, Falcimagne R, Berbigier P, Bonnefond JM, Ceschia E, D'Hour P, Henault C, Laville P, Martin C, Pinares-Patino C (2007) The role of grazing management for the net biome productivity and greenhouse gas budget ($CO_2$, $N_2O$ and $CH_4$) of semi-natural grassland. Agric Ecosyst Environ 121:47–58

Anger M, Hoffmann C, Kuhbauch W (2003) Nitrous oxide emissions from artificial urine patches applied to different N-fertilized swards and estimated annual $N_2O$ emissions for differently fertilized pastures in an upland location in Germany. Soil Use Manag 19:104–111

Brock C, Barham B (2009) Farm structural change of a different kind: alternative dairy farms in Wisconsin—graziers, organic and Amish. Renew Agric Food Syst 24:25–37

Cameron KC, Di HJ, Moir JL (2013) Nitrogen losses from the soil/plant system: a review. Ann Appl Biol 162:145–173

Chapuis-Lardy L, Wrage N, Metay A, Chotte JL, Bernoux M (2007) Soils, a sink for $N_2O$? A review. Glob Change Biol 13:1–17

Conant RT, Paustian K (2002) Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochem Cycles 16:1143

Conant RT, Paustian K, Elliott ET (2001) Grassland management and conversion into grassland: effects on soil carbon. Ecol Appl 11:343–355

Conant RT, Paustian K, Del Grosso SJ, Parton WJ (2005) Nitrogen pools and fluxes in grassland soils sequestering carbon. Nutr Cycl Agroecosyst 71:239–248

Crawley MJ (2002) Statistical computing: an introduction to data analysis using S-Plus. Wiley, New York, p 756

De Vries FT, Bardgett RD (2012) Plant-microbial linkages and ecosystem nitrogen retention: lessons for sustainable agriculture. Front Ecol Environ 10:425–432

Duran BEL, Kucharik CJ (2013) Comparison of two chamber methods for measuring soil trace-gas fluxes in bioenergy cropping systems. Soil Sci Soc Am J 77:1601–1612

Flechard CR, Neftel A, Jocher M, Ammann C, Fuhrer J (2005) Bi-directional soil/atmosphere $N_2O$ exchange over two mown grassland systems with contrasting management practices. Glob Change Biol 11:2114–2127

Follett RF, Kimble JM, Lal R (2001) The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. Lewis Publishers, New York

Greenquist MA, Klopfenstein TJ, Schacht WH, Erickson GE, Pol KJV, Luebbe MK, Brink KR, Swartz AK, Baleseng LB (2009) Effects of nitrogen fertilization and dried distillers grains supplementation: forage use and performance of yearling steer. J Anim Sci 87:3639–3646

Greenquist MA, Schwarz AK, Klopfenstein TJ, Schacht WH, Erickson GE, Pol KJV, Luebbe MK, Brink KR, Baleseng LB (2011) Effects of nitrogen fertilization and dried distillers grains supplementation: nitorgen use efficiency. J Anim Sci 89:1146–1152

Groffman PM, Altabet MA, Bohlke JK, Butterbach-Bahl K, David MB, Firestone MK, Giblin AE, Kana TM, Nielsen LP, Voytek MA (2006) Methods for measuring denitrification: diverse approaches to a difficult problem. Ecol Appl 16:2091–2122

Hamilton EW, Frank DA, Hinchey PM, Murray TR (2008) Defoliation induces root exudation and triggers positive rhizospheric feedbacks in a temperate grassland. Soil Biol Biochem 40:2865–2873

Holland EA, Robertson GP, Greenberg J, Groffman P, Boone R, Gosz J (1999) Soil $CO_2$, $N_2O$, and $CH_4$ exchange. In: Robertson GP, Bledsoe CS, Coleman DC, Sollins P (eds) Standard soil methods for long-term ecological research. Oxford University Press, New York, pp 185–201

Houlbrooke DJ, Laurenson S (2013) Effect of sheep and cattle treading damage on soil microporosity and soil water holding capacity. Agric Water Manag 121:81–84

Houlbrooke DJ, Paton RJ, Littlejohn RP, Morton JD (2011) Land-use intensification in New Zealand: effects on soil properties and pasture production. J Agric Sci 149:337–349

Hutchinson G, Livingston G (2002) Vents and seals in non-steady-state chambers used for measuring gas exchange between soil and the atmosphere. Eur J Soil Sci 52:675–682

Hyde BP, Hawkins MJ, Fanning AF, Noonan D, Ryan M, O'Toole P, Carton OT (2006) Nitrous oxide emissions from a fertilized and grazed grassland in the South East of Ireland. Nutr Cycl Agroecosyst 75:187–200

Hynst J, Simek M, Brucek P, Petersen SO (2007) High fluxes but different patterns of nitrous oxide and carbon dioxide emissions from soil in a cattle overwintering area. Agric Ecosyst Environ 120:269–279

IPCC (2001) Climate change 2001, the scientific basis. In: Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge

IPCC (2013) Climate change 2013, the physical science basis. In: Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge

Jackson RD, Bell MM, Gratton C (2007) Assessing ecosystem variance at different scales to generalize about pasture management in southern Wisconsin. Agric Ecosyst Environ 122:471–478

Jackson-Smith D, Barham BL, Nevius M, Klemme R (1996) Grazing in Dairyland: the use and performance of management intensive rotational grazing among Wisconsin dairy farms ATFFI technical report, #5. Agriculture Technology and Family Farm Institute, University of Wisconsin-Madison, Madison

Klopfenstein TJ, Mass RA, Creighton KW, Patterson HH (2001) Estimating forage protein degradation in the rumen. J Anim Sci 79(E. Suppl.):E208–E217

Koops JG, vanBeusichem ML, Oenema O (1997) Nitrous oxide production, its source and distribution in urine patches on grassland on peat soil. Plant Soil 191:57–65

Lake RP, Hildebrand RL, Clanton DC (1974) Limited energy supplementation of yearling steers grazing irrigated pasture and subsequent feedlot performance. J Anim Sci 39:827–833

Livesley SJ, Kiese R, Graham J, Weston CJ, Butterbach-Bahl K, Arndt SK (2008) Trace gas flux and the influence of short-term soil water and temperature dynamics in Australian sheep grazed pastures of differing productivity. Plant Soil 309:89–103

Livingston GP, Hutchinson GL (1994) Enclosure-based measurement of trace gas exchange: applications and sources of error. In: Matson PA, Harriss RC (eds) Methods in ecology: biogenic trace gas emissions from soil and water. Blackwell Scientific, London, pp 14–51

Loy TW, Klopfenstein TJ, Erickson GE, Griffin WA (2007) Effects of dried distillers grains and equivalent undegradable intake protein or ether extract on performance and forage intake of heifers grazing smooth bromegrass pastures. J Anim Sci 85:2614–2624

Luo J, Tillman RW, Ball PR (2000) Nitrogen loss through denitrification in a soil under pasture in New Zealand. Soil Biol Biochem 32:497–509

Morris SE, Klopfenstein TJ, Adams DC, Erickson GE, Pol KJV (2005) The effects of dried distillers grains on heifers consuming low and high quality forage. In: Nebraska Beef Cattle Report 83A, pp 18–20

Morris SE, MacDonald JC, Adams DC, Klopfenstein TJ, Davis RL, Teichert JR (2006) Effects of supplanting dried distillers grains to steers grazing summer sandhill range. In: Nebraska Beef Cattle Report 88A, pp 30–32

Mosier AR (2001) Exchange of gaseous nitrogen compounds between agricultural systems and the atmosphere. Plant Soil 228:17–27

Mosier AR, Morgan JA, King JY, LeCain D, Milchunas DG (2002) Soil-atmosphere exchange of $CH_4$, $CO_2$, $NO_x$, and $N_2O$ in the Colorado shortgrass steppe under elevated $CO_2$. Plant Soil 240:201–211

Oates LG, Undersander DJ, Gratton C, Bell MM, Jackson RD (2011) Management-intensive rotational grazing enhances forage production and quality of subhumid cool-season pastures. Crop Sci 51(2):892–901

Oenema O, Wrage N, Velthof GL, van Groenigen JW, Dolfing J, Kuikman PJ (2005) Trends in global nitrous oxide emissions from animal production systems. Nutr Cycl Agroecosyst 72:51–65

Ostrom M, Jackson-Smith D (2000) The use and performance of management intensive rotational grazing among Wisconsin dairy farms in the 1990s research report no. 8, Program on Agricultural Technology Studies, University of Wisconsin-Madison

Paine LK, Klemme RM, Undersander DJ, Welsh M (2000) Wisconsin's grazing networks: history, structure, and function. J Nat Resour Life Sci Educ 29:60–67

Rehm GW, Moline WJ, Schwartz EJ, Moomaw RS (1971) The effect of fertilization and management on the production of bromegrass in northeastern Nebraska. University of Nebraska-Lincoln. Res Stn Bull 247:3–27

Robertson GP (1999) Standard soil methods for long-term ecological research. Oxford University Press, New York

Ross DJ, Speir TW, Kettles HA, Tate KR, Mackay AD (1995) Soil microbial biomass, C and N mineralization, and enzyme activities in a hill pasture: influence of grazing management. Aust J Soil Res 33:943–959

Ruzjerez BE, White RE, Ball PR (1994) Long-term measurement of denitrification in three contrasting pastures grazed by sheep. Soil Biol Biochem 26:29–39

Schlueter KR (2004) Seasonal dry matter and crude protein removal by grazing from grass/legume mixtures. University of Nebraska-Lincoln, Lincoln

Simek M, Elhottova D, Klimes F, Hopkins DW (2004) Emissions of $N_2O$ and $CO_2$, denitrification measurements and soil properties in red clover and ryegrass stands. Soil Biol Biochem 36:9–21

Uchida Y, Clough TJ, Kelliher FM, Sherlock RR (2008) Effects of aggregate size, soil compaction, and bovine urine on $N_2O$ emissions from a pasture soil. Soil Biol Biochem 40:924–931

van Groenigen JW, Velthof GL, van der Bolt FJE, Vos A, Kuikman PJ (2005) Seasonal variation in $N_2O$ emissions from urine patches: effects of urine concentration, soil compaction and dung. Plant Soil 273:15–27

Velthof GL, Jarvis SC, Stein A, Allen AG, Oenema O (1996a) Spatial variability of nitrous oxide fluxes in mown and grazed grasslands on a poorly drained clay soil. Soil Biol Biochem 28:1215–1225

Velthof GL, Brader AB, Oenema O (1996b) Seasonal variations in nitrous oxide losses from managed grasslands in The Netherlands. Plant Soil 181:263–274

Waller SS, Moser LE, Anderson B (1986) A guide for planning and analyzing a year-round forage program. Nebraska Cooperative Extension EC 86-113-C

Williams PH, Jarvis SC, Dixon E (1998) Emission of nitric oxide and nitrous oxide from soil under field and laboratory conditions. Soil Biol Biochem 30:1885–1893