



Nitrous oxide emission factors for cattle dung and urine deposited onto tropical pastures: A review of field-based studies

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ARTICLE INFO

Keywords:

Nitrous oxide
Cattle excreta
Dry/wet climate
Tropics
IPCC refinement

ABSTRACT

Livestock excreta on pastures is an important source of nitrous oxide (N₂O) emissions, however studies measuring these emissions in tropical regions, particularly Africa, remain limited. Therefore we measured N₂O emissions from different quantities of dung patches during three observation periods (dry, wet and transition from dry to wet season) and different volumes of urine patches during wet and dry seasons. Dung patches did not stimulate soil N₂O emissions in any of the three observation periods, while urine application stimulated soil N₂O emissions during both seasons, with higher emissions observed during the wet season. The dung EFs (0.00–0.03%) and the urine EFs (0.04–0.40%) showed no detectable effects of dung quantity or urine volume. We further synthesized observations from other studies in wet and dry tropical regions, which indicated that the excreta N₂O EFs were similar to the default values provided in the IPCC 2019 refinement (0.11% vs 0.07% for dung and 0.41% vs 0.32% for urine in dry climates, and 0.13% vs 0.13% for dung and 0.65% vs 0.77% for urine in wet climates). However, sub-Saharan African (SSA) studies had consistently lower EFs, possibly due to the lower urine-N: dung-N ratio in SSA compared with the other tropical regions, suggesting that the refinement may still overestimate excreta emissions in SSA. Moreover, considering the large variations in the summarized tropical excreta N₂O EFs, from -0.01 to 1.77% for dung and 0.00 to 4.90% for urine, more studies under diverse conditions across tropical regions are recommended.

1. Introduction

Grasslands used for livestock grazing are important nitrous oxide (N₂O) sources (Jones et al., 2005). Estimated global N₂O emissions from livestock excreta deposition on managed grasslands were 1.31 Tg N₂O-N in 2014 (Dangal et al., 2019) and are expected to increase in the future due to increased livestock numbers and higher stocking rates (Tian et al., 2020; Smith et al., 2016). The high amount of nitrogen (N) deposited on a small area (e.g. 16 g N in 0.35 m² for urine and 9 g N on 0.08 m² for dung) during cattle defecation lead to high localized N loading rates, equivalent to 113 g N m⁻² for dung and between 47 and 61 g N m⁻² for urine (Saarijärvi et al., 2006; Selbie et al., 2015), which greatly exceeds plant utilization rates (Cai et al., 2017). Stimulation of soil N₂O emissions following livestock excreta deposition to grasslands are therefore due to the increased soil N availability for microbial processes involved

in N₂O production (e.g. nitrification and denitrification).

The Tier 1 approach has been developed by the Intergovernmental Panel on Climate Change (IPCC) to help jurisdictions that lacked sufficient information for the development of local emission factors estimate N₂O emissions from livestock excreta deposition (IPCC, 2006). The IPCC then developed a set of refinements with disaggregated EFs for urine and dung for both cattle and sheep under wet and dry climates to reduce uncertainties (Kristell et al., 2019).

Globally, about 60% of the N excretions and N₂O emissions from animal production systems are due to cattle (Van Groenigen et al., 2005). Africa, particularly sub-Saharan Africa (SSA) and Latin America (LAM) are home to more than 40% of the world's cattle, with the majority of these grazed on grassland (Butterbach-Bahl et al., 2020; Mazzeo et al., 2014). Even though livestock excreta deposition is an important N₂O emission source in SSA and LAM (de Bastos et al., 2020;

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<https://doi.org/10.1016/j.agee.2021.107637>

Received 9 June 2021; Received in revised form 16 August 2021; Accepted 21 August 2021

Available online 2 September 2021

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Tully et al., 2017), the studies used in the IPCC 2019 refinement were mostly from temperate regions, with only two studies from Kenya and seven studies from Brazil, which likely results in high uncertainty for emission estimates from these regions.

Furthermore, the N partitioning between urine and dung in the tropics was estimated to be near 40:60 by Rufino et al. (2006), which deviates significantly from the 60:40 split used by the IPCC 2019 refinement, which was based on a summary of trials primarily from New Zealand (Kelliher et al., 2014). Marked differences in N partitioning may result in large uncertainties in excreta N₂O emissions in regional assessments due to the higher N availability and subsequent higher N₂O EFs in urine (Cai and Akiyama, 2016). Besides, the IPCC 2019 refinement did not consider the effect of soil properties on N₂O emissions from excreta patches. However, soil properties have been found to influence soil N₂O emissions after urine application (Zhu et al., 2020a). Also, Kelliher et al. (2014) reported that soils in terrain with slopes >12° had lower excreta N₂O EF than soils on flat terrain. Hence, there is some uncertainty as to how applicable the EF recommended in the 2019 IPCC refinement are for tropical regions, especially SSA and LAM. To address this uncertainty, reliable data sets are required to develop country- or region-specific emission factors and to better assess the emissions from livestock production systems in tropical regions.

Therefore, we measured how dung and urine application rates affect N₂O EFs based on a field study in Kenya, while also synthesizing existing data on these EFs for tropical regions in order to determine whether the new N₂O EFs in the 2019 IPCC refinement are appropriate for urine and dung excreted on tropical pastures, particularly in SSA.

2. Materials and methods

2.1. Experimental design

The field experiment was conducted at the International Livestock Research Institute (ILRI) research farm, Nairobi, Kenya (S 1°16'13"; E 36°43'23"; altitude 1809 m asl). A detailed site description can be found in Zhu et al. (2020b). Briefly, the pasture is predominantly a mix of Kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.) and Rhodes grass (*Chloris gayana* Kunth). The grass was cut to 5 cm by hand every two to three weeks during the wet season. During the dry season the grass did not need to be cut. The soil at the experimental site is a well-drained, deep humic nitisol, with 62.7% clay and 24% sand. The C content is 22.59 ± 0.50 g C kg⁻¹ and the N content is 2.22 ± 0.04 g N kg⁻¹ in the top soils (0–0.10 m depth). The soil pH (water) was 6.8, while the bulk density was 1.07 ± 0.03 g cm⁻³.

To determine excreta effects on soil N₂O emissions, two experiments were set up. In experiment 1, dung quantity effects on N₂O emissions and EFs were tested in six treatments through the application of three quantities of cattle dung (either 0.5, 1.0 and 1.5 kg fresh dung) and two quantities of cattle excreta (dung and urine mixed) that had been digested in a biogas digester ("bioslurry", 0.87 vs 1.735 kg in Trial 1, 0.72 vs 1.45 kg in Trial 2 and 0.919 vs 1.838 kg in Trial 3) compared with a no application ("control"). In experiment 2, the effect of urine volume on N₂O emissions was determined by comparing N₂O flux rates from six treatments (a control [no application], 0.5 L distilled water, 2.0 L distilled water, 0.5 L urine, 1.25 L urine, and 2.0 L urine). Each treatment in both experiments consisted of three spatial replicates. The experiments were repeated at different times of the year. For the dung quantity experiment, the first trial was conducted from 11 April to 18 May 2017 (Trial 1, dung rainy season), the second trial from 01 June to 04 July 2017 (Trial 2, dung transition period) and the third trial from 17 July to 24 August, 2017 (Trial 3, dung dry season). For the urine volume experiment, two trials were conducted from 24 May to 04 September 2018 (Trial 4, urine rainy season) and 24 September to 30 November 2019 (Trial 5, urine dry season). Each trial ended after N₂O fluxes in the treated plots were similar to N₂O fluxes measured in the control plots for a period of at least two weeks. The amount of dung and the volume of

urine were determined in a previous animal feeding trial where freely grazing cattle and cattle fed at different maintenance energy requirement levels were monitored (Zhu et al., 2020b, 2018). To our knowledge, this is the study first to examine the effects of bioslurry additions and urine volume on N₂O emissions to tropical rangelands in SSA. The dung was collected in the morning before application from a barn where Boran steers (*Bos indicus*) that had spent the previous day grazing pasture (a mixture of Kikuyu and Rhodes grass). Approximately twelve kg of dung was collected and mixed to ensure homogeneity. A small (1.0 kg) sub-sample was set aside for analysis, while the rest was used to apply to the pasture as described above. Urine was collected from penned steers (ca. 1 year old) fitted with urine collection harnesses. The individual urine samples were then mixed together to form a single composite sample with an acidified sub-sample set aside for later analysis. The bioslurry was collected with a bucket the same day of application, from the discharge of a small (12 m³) biodigester located on the ILRI farm with the feedstock being the manure from the same cattle described above. Then fresh bioslurry was then mixed well and applied accordingly, with 1.0 kg sub-sample set aside for further analysis. Bioslurry and dung total C and N content were determined on an elemental combustion system (Vario Max C/N Analyzer, Elementar Analysensysteme GmbH, Hanau, Germany), while the water content was determined by oven-drying at 55 °C until constant weight. Urine N concentration was determined via Kjeldahl digestion followed by colorimetry on an ultraviolet spectrophotometer.

Soil N₂O fluxes were measured using an automated static chamber system (Butterbach-Bahl et al., 1997), consisting of 18 individual chambers divided into six blocks of three chambers, and an automated gas sampling system that was connected to a cavity ringdown laser absorption spectrometer (G2308, Picarro Inc., Santa Clara, CA, USA). The individual chambers were placed approximately 0.5 m apart from each other. Each block of three chambers was closed and sampled for 45 min with changes in the mixing ratios of the headspace monitored sequentially in 1-min intervals during deployment. After the 45 min measurement period, the chambers were re-opened and the next block was closed and sampled. A measurement cycle therefore consisted of $45 \times 6 + 7 = 277$ min for all 18 chambers. Chambers were moved after each trial to unaffected grassland to avoid potential legacy effects on N₂O fluxes of the prior excreta residues. To maintain chamber measurement integrity, soil moisture was only recorded outside of the chambers at 0.05 m soil depth with the Decagon 5TM sensors every 5 min to represent the soil moisture across all treatments.

2.2. Data collection of excreta N₂O EF in tropics

Peer-reviewed publications were collected by searching Scopus with the keywords "urine" or "dung" or "excreta" and "N₂O" and "soil" from 1990 to August 2020. From these publications, only field studies from the tropics and subtropics were included. Including this study, we found 20 studies that reported N₂O emissions from excreta deposition onto tropical pastures, with a total of 170 measurements, including 14 studies with 85 measurements on cattle dung, 16 studies with 68 measurements on cattle urine, 2 studies with 3 measurements on sheep dung, and 2 studies with 14 measurements on sheep urine (Supplementary material Fig. S1). Although 7 studies had observations for less than the 30 days recommended by the IPCC, we still kept those in our dataset due to the limited number of available field studies. The climate for the different tropical study sites was classified as "wet" if annual precipitation exceeded 1000 mm and dry if the annual precipitation was less than 1000 mm, as per the IPCC 2019 refinement (Kristell et al., 2019).

2.3. Data analyses

Differences between seasons in the properties (e.g. water content, C and N concentration and C/N ratio) of the fresh dung and the urine N concentrations were tested using a one-way ANOVA with Tukey's HSD

Table 1

Dung and bioslurry water content, carbon and nitrogen concentrations, and urine N concentration applied to grassland at the International Livestock Research Institute near Nairobi, Kenya.

Period	Season	Type	Dung, bioslurry and urine property parameters			
			Water content (%)	C _{conc} (g kg ⁻¹ DM)	N _{conc} (g kg ⁻¹ DM/g L ⁻¹)	C/N ratio
2017.04.11–2017.05.18	Wet season	Dung	77.1 ± 1.2a	405.3 ± 0.5a	10.5 ± 0.2a	38.6 ± 0.7a
		Bioslurry	83.8 ± 3.2b	367.6 ± 3.6b	19.6 ± 0.4b	18.8 ± 0.4b
2017.06.01–2017.07.04	Transition period	Dung	78.7 ± 2.9a	408.1 ± 0.5a	12.3 ± 0.5a	33.3 ± 1.2a
		Bioslurry	85.4 ± 2.2b	369.9 ± 0.1b	20.9 ± 0.2b	17.7 ± 0.2b
2017.07.17–2017.08.24	Dry season	Dung	81.9 ± 0.3a	368.5 ± 2.5a	17.7 ± 0.3a	20.8 ± 0.5a
		Bioslurry	90.2 ± 0.0b	359.4 ± 3.5b	21.9 ± 0.6b	16.5 ± 0.6b
2018.05.20–2018.09.04	Wet season	Urine			4.43 ± 0.30A	
2019.09.20–2019.11.30	Dry season	Urine			5.65 ± 0.11B	

Note: Values are mean ± 1 standard deviation (n = 3); Different lowercase letters indicate significant differences between dung and bioslurry properties within each season and different uppercase letters indicate significant differences for urine N concentration among seasons ($P < 0.05$). DM: dry matter.

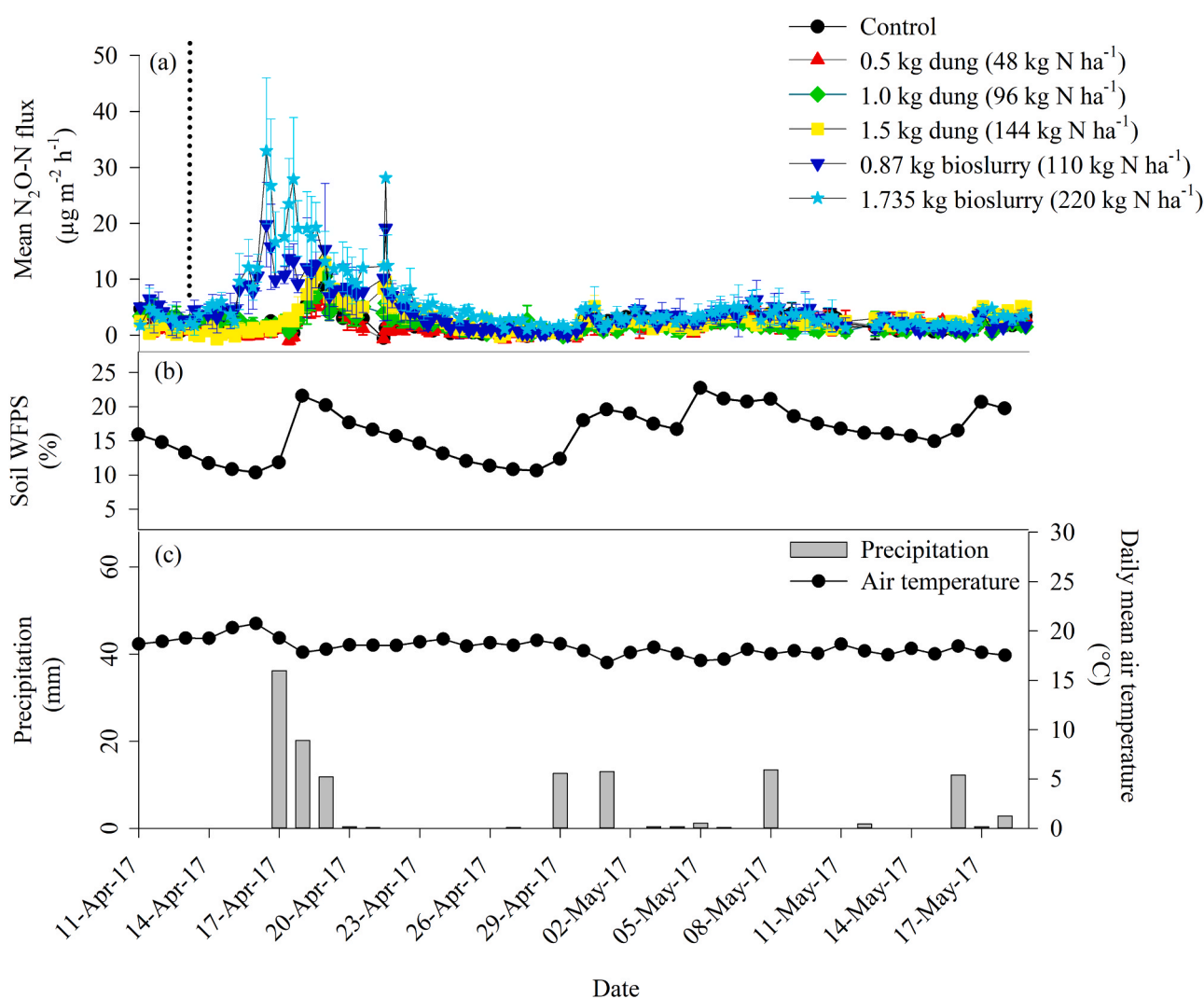


Fig. 1. The N₂O-N fluxes over time as affected by additions of different amounts of dung or bioslurry to grassland during the wet season, along with the temporal dynamics of mean daily soil moisture at 0.05 m depth (b) and air temperature and the daily precipitation (c) at the study site. Each flux value represents the mean of three chambers (±SE), with fluxes observed in six hour time intervals. Dotted vertical lines indicate application of the excreta.

test. Differences in N₂O EFs between the dung quantities or urine volumes were tested with a two-way ANOVA using treatment (e.g. quantity or volume) and season as fixed factors. Differences between seasons in the N₂O EF for cattle urine and dung from the synthesized data were also tested using one-way ANOVA with Tukey's HSD test. All data were tested for normality using Shapiro-Wilk and were log-transformed when necessary. All statistical calculations were done in R v3.5.3 (R core team,

2019). A linear regression analysis between dung/urine EF and excreta application rates, N concentration and soil pH was conducted with Sigmaplot 12.5 (Systat Software, Inc. SigmaPlot for Windows).

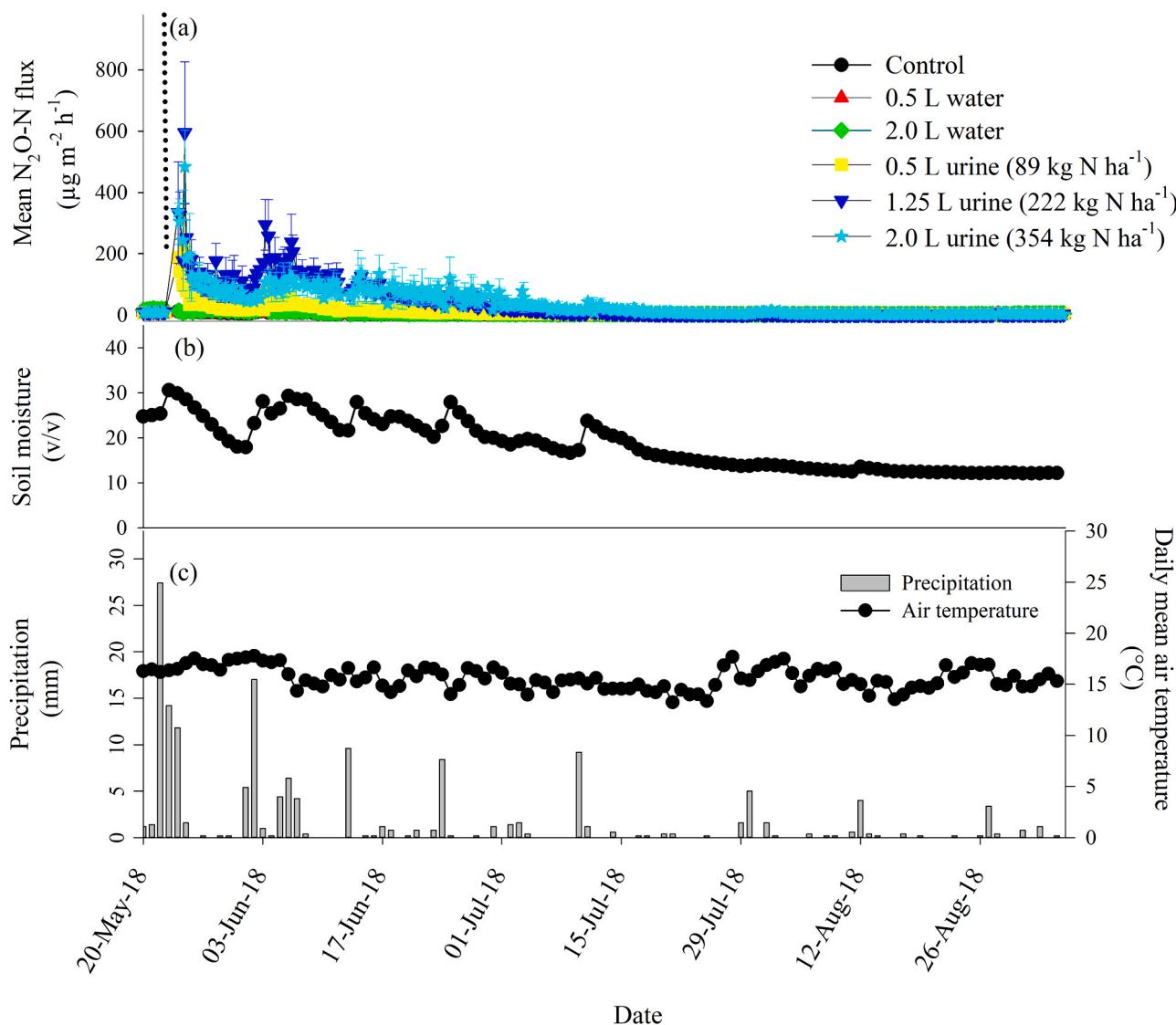


Fig. 2. The N_2O -N fluxes over time as affected by additions of different volumes of urine to grassland during the wet season, along with the temporal dynamics of mean daily soil moisture at 0.05 m depth (b) and air temperature and the daily precipitation (c) at the study site. Each flux value represents the mean of three chambers (\pm SE), with fluxes observed in six hour time intervals. Dotted vertical lines indicate application of the excreta.

3. Results

3.1. Feed diet effects on dung and urine property

We only report significant differences except when explicitly stated otherwise. Results of the ANOVA analysis can be found in Table 1. In our study, chemical composition of the dung was different between seasons, with lower N concentrations ($10.5 \pm 0.2 \text{ g kg}^{-1}$ dry matter) and higher C/N ratios (38.6 ± 0.7) in the wet season, while N concentrations were higher ($17.7 \pm 0.3 \text{ g kg}^{-1}$ dry matter) and C/N ratios lower (20.8 ± 0.5) in the dry season. The urine N concentration was also lower during the wet season ($4.43 \pm 0.30 \text{ g N L}^{-1}$) than during the dry season ($5.65 \pm 0.11 \text{ g N L}^{-1}$).

3.2. Effect of excreta additions on soil N_2O fluxes

In our experiment, the dung application treatment had no measurable impact on soil N_2O fluxes across all three trials (application rates from 48 to 192 kg N ha^{-1}) as all observed N_2O fluxes were similar to the control. Instead, N_2O fluxes were related predominantly to rainfall events (Fig. 1, S8 and S9). The N_2O EFs ranged from 0.00% to 0.03% for

the dung applications, with no detectable effect of dung quantity across all three periods ($P > 0.05$). Although small increases in soil N_2O fluxes were observed after bioslurry application, the N_2O EFs of bioslurry were similar to those of the dung patches (Fig. 1, Supplementary material Table 1).

In contrast, the urine application, with application rates from 89 to 452 kg N ha^{-1} , increased N_2O fluxes during both the dry and the wet season (Fig. 2, S10). The highest N_2O flux during the wet season ($594 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$) was almost six times larger than that observed during the dry season ($108 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$). The N_2O fluxes were also stimulated by heavy precipitation (Fig. 2, S10). Urine patch N_2O EFs were similar across the different volumes. Consistent with the pattern observed for emissions, the N_2O EFs was higher when urine was applied during the wet season (0.22–0.40%) compared to the dry season (0.04–0.07%, $P = 0.001$, Supplementary material Table 2).

3.3. Summary of excreta-derived N_2O emissions in tropical regions

The synthesis of published data from tropical and subtropical regions showed that the N application rate for cattle dung patches ranged from 49 to 1300 kg N ha^{-1} , with a mean of 303 kg N ha^{-1} and 85% of the

Table 2

Number, reference, year published, location, observation period, excreta type, N application rate and N₂O emission factors of available studies that investigated N₂O emissions from excreta applied to tropical rangelands.

No.	Reference	Year	Location	Observation period (days)	Excreta type	N application rate (kg N ha ⁻¹)	N ₂ O emission factor (%)
1	This study	2020	Kenya	31	Cattle dung	48–226	-0.01–0.03
				68–104	Cattle urine	89–452	0.04–0.40
2	Sordi et al. (2014)	2014	Brazil	90	Cattle dung	52–188	0.09–0.40
					Cattle urine	89–392	0.10–0.45
3	Mazzetto et al. (2014)	2014	Brazil	30	Cattle dung	1300	-0.00–0.02
4	Lessa et al. (2014)	2014	Brazil	37–94	Cattle dung	171–188	0.00–0.16
					Cattle urine	267–421	0.01–2.55
5	Cardoso et al. (2016)	2016	Brazil	14	Cattle dung	147–294	0.15–0.21
				43	Cattle urine	329–658	2.43–4.90
6	Pelster et al. (2016)	2016	Kenya	28	Cattle dung	197–352	0.04–0.36
					Cattle urine	69–71	0.64–1.39
7	Tully et al. (2017)	2017	Kenya	60–63	Cattle dung	240	0.00–0.04
					Cattle urine	1090	0.05–0.21
8	Simon et al. (2018)	2018	Brazil	60–68	Cattle dung	516–562	0.04–0.23
					Cattle urine	176–256	0.19–0.45
9	Zhu et al. (2018)	2018	Kenya	25–29	Cattle dung	49–131	-0.01–0.01
10	Cardoso et al. (2019)	2019	Brazil	105	Cattle dung	164–280	0.15–0.58
					Cattle urine	440	0.32–1.20
11	Rivera et al. (2019)	2019	Colombia	26	Cattle dung	–	1.37–1.77
					Cattle urine	–	0.30–3.47
12	Zhu et al. (2020)	2020	Kenya	25–73	Cattle dung	270–393	0.00–0.20
				39–73	Cattle urine	715–807	0.01–1.36
13	Bretas et al. (2020)	2020	Brazil	78–89	Cattle dung	665–837	0.00–0.06
					Cattle urine	102–403	0.04–0.39
14	Zhu et al. (2020)	2020	Kenya	42–59	Cattle dung	90–132	0.02–0.12
					Cattle urine	61–81	0.03–0.25
15	Barneze et al. (2014)	2014	Brazil	30	Cattle urine	859	0.20
16	Mazzetto et al. (2015)	2015	Brazil	30	Cattle urine	360	0.08–0.38
17	Byrnes et al. (2017)	2017	Colombia	29	Cattle urine	1230	0.00–0.07
18	Chirinda et al. (2019)	2019	Nicaragua	20	Cattle urine	464	0.37–1.23
			Colombia	10–20		112–789	0.01–0.46
			Brazil	20		619	0.48–0.72
			Argentina	20		546	0.02
19	Tomazi et al. (2015)	2015	Brazil	39	Sheep dung	13	0.06
					Sheep urine	161–403	0.22–0.31
20	Bastos et al. (2020)	2020	Brazil	40	Sheep dung	76–81	0.01–0.05
					Sheep urine	96–478	0.06–0.34

values <500 kg N ha⁻¹ (Table 2). The N application rate for urine patches ranged from 61 to 1230 kg N ha⁻¹, with a mean application rate of 436 kg N ha⁻¹ and 66% of the values <500 kg N ha⁻¹. Dung N₂O EFs ranged from -0.01 to 1.77%, while urine N₂O EFs ranged from 0.00% to 4.90%. There was no detectable relationship between N application rates or urine N concentrations and N₂O EFs ($P > 0.05$, Supplementary Figs. S2–5). However, a positive linear correlation was found between dung N concentration and dung N₂O EF ($P = 0.0003$, Supplementary S2).

The mean (± 1 standard deviation) N₂O EFs (%) for cattle dung and urine on tropical pastures were 0.14 ± 0.03 and 0.48 ± 0.03 , respectively. Following climatic division as per the IPCC 2019 refinement, the cattle dung N₂O EFs (%) were 0.11 ± 0.04 in dry climates and 0.13 ± 0.15 in wet climates, while for cattle urine the EFs were 0.41 ± 0.14 for dry and 0.65 ± 0.16 for wet climates (Fig. 3). However, the mean cattle dung and urine N₂O EFs (%) were considerably lower in SSA (0.05 ± 0.01 and 0.32 ± 0.09 for dung and urine, respectively) compared to LAM (0.23 ± 0.07 and 0.67 ± 0.16 for dung and urine, respectively). The mean N₂O EFs (%) for sheep were 0.04 ± 0.03 for dung and 0.23 ± 0.09 for urine with both studies conducted in Brazil (Table 2, Fig. 3).

4. Discussion

4.1. Influence of excreta chemical composition and excreta N partitioning

Animal diet, which substantially differs between dry and wet seasons in tropical regions (Onyango et al., 2019), is known to influence the urine and dung N concentrations (Dijkstra et al., 2013). Feed quality and

quantity also influences the amount of dung and urine excreted per dropping, as well as the total N excretion per animal. A cattle feeding trial in Kenya where animals were fed at or below their maintenance energy requirements reported that daily urine volume was positively correlated with feed intake while the urine N concentration remained unchanged, resulting in greater total urine N excretion with increased feed levels (Wassie et al., 2019). They also found that the N excretion via dung increased with increasing feed intake due to greater total daily dung excretion rates and higher dung N concentrations (Wassie et al., 2019; Zhu et al., 2018).

Greater N intake also increases the proportion of N excreted as urine compared to dung (Dijkstra et al., 2013). As the urine N₂O EFs are generally higher than the dung N₂O EFs (Cai and Akiyama, 2016), developing disaggregated N₂O EFs for urine and dung is recommended. Indeed, the IPCC 2019 refinement uses disaggregated N₂O EFs for urine and dung along with a fixed value for N partitioning between urine and dung of 66:34. The protein- and energy-rich cattle diets typically found across the “Global North”, where diets are tailored to maximize animal productivity, causes the N split between urine and dung to be about 60:40 (Chadwick et al., 2018). In Brazil this ratio ranges from 60:40–50:50 (Lessa et al., 2014), whereas the urine-N: dung-N ratio in SSA is estimated to be near 40:60 (Rufino et al., 2006) due to the overall low nutritional value of feeds and frequent episodes of feed scarcity e.g. during dry seasons in SSA. There, urine-N: dung-N ratios as low as 13:87 were reported from cattle fed on wheat straw hay (Korir et al., 2016), and 33:67–50:50 from cattle fed on Rhodes grass hay at different metabolic energy requirements (Wassie et al., 2019). Therefore, to more accurately estimate excreta N₂O emissions, not only are separate dung and urine N₂O EFs required, but also the total amount of N excreted via

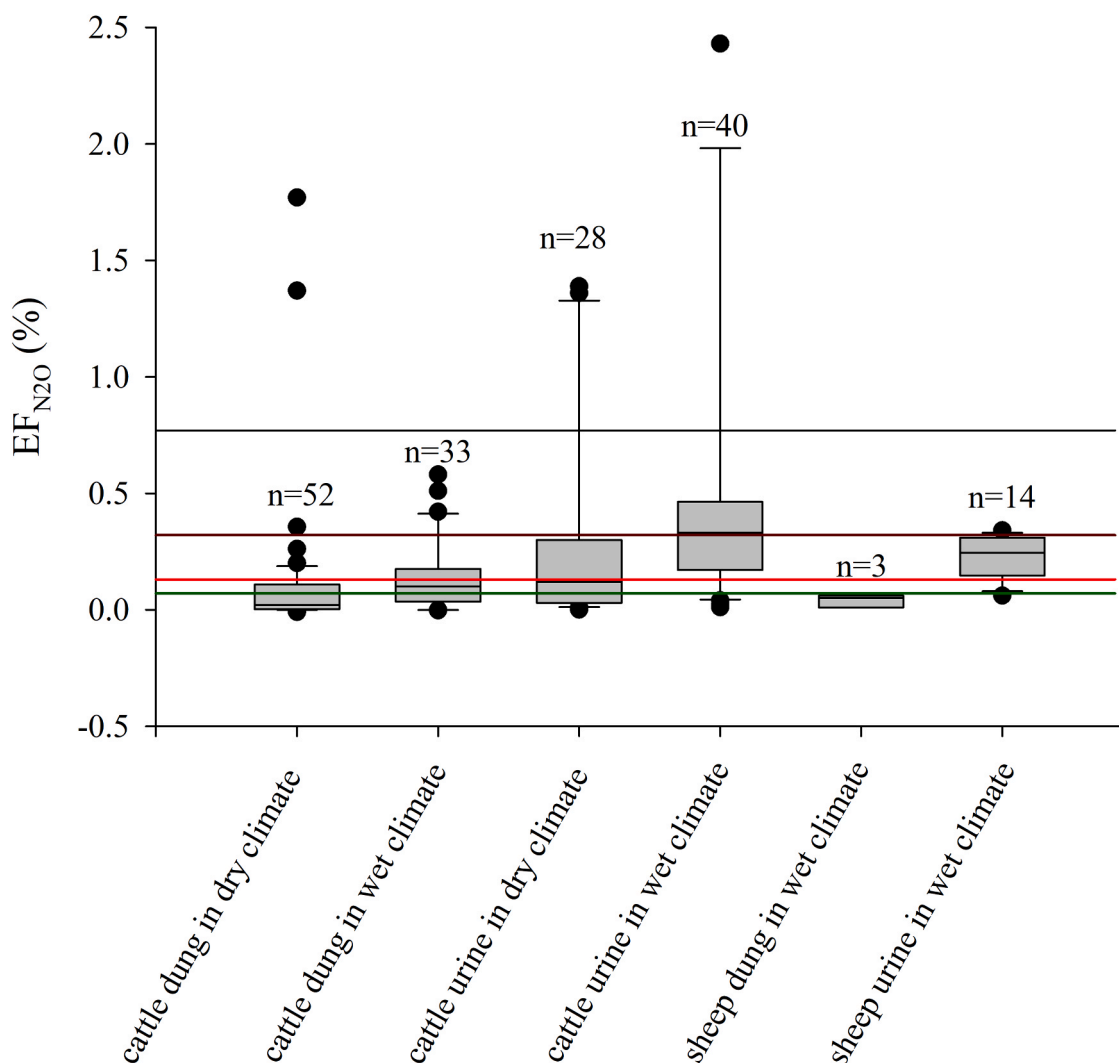


Fig. 3. N₂O emission factors for different cattle and sheep excreta types applied to tropical grassland under dry or wet climates in previous as well as our studies. Note: The horizontal lines indicate the Intergovernmental Panel on Climate Change 2019 Refinement default values for N₂O EFs from cattle urine and dung under dry or wet climate.

the urinary or dung pathway. Since the application rates of dung and urine in our experiments had no measurable effect on N₂O EFs, annual excretion rates should be sufficient to determine emissions.

To our knowledge, our study is the first examining the effect of bioslurry additions to tropical rangelands on N₂O emissions. However, this is an important feature as there is a strong push by development agencies to motivate smallholders to install biogas plants with the number of small-scale biogas plants in Kenya estimated to be 16,419 (Muturi et al., 2021). Farmers who have small scale biogas plants usually spread the slurry to adjacent pasture (Smith et al., 2014). The EF_{N₂O} we found for bioslurry were comparable to those we found for dung patches (Supplementary Material Table 1), which could be ascribed to the quick drying due to the relative low humidity and high solar radiation in Kenya (Zhu et al., 2018). In addition, urine volume did not influence the urine N₂O EFs which was in contrast with a study in Brazil (Sordi et al., 2014). This could be because of the higher ammonia volatilization and higher leaching from greater urine application rates (Zhu et al., 2020b).

4.2. Application time and soil effect on excreta N₂O EFs

From the synthesized data, we did not find that N₂O EFs were always related to seasonality. This is inconsistent with our field study, which showed higher urine N₂O EFs in wet season compared to the dry season.

More precipitation in the wet season may favor N₂O production via increasing soil moisture (Marsden et al., 2016), however more precipitation may also lead to higher NO₃⁻ leaching and higher rates of complete denitrification, thus decreasing N₂O production (Zhu et al., 2020b). Therefore, measurements with high temporal resolution in both dry and wet seasons are essential to evaluate annual N₂O emissions.

No significant relationships were detected between excreta N₂O EFs and soil pH (Supplementary material Figs. S6–7). However, soil type is often overlooked as an important component for differences in excreta N₂O EFs, especially for urine. Zhu et al. (2020a) reported that although the dung N₂O EFs were similar across five different soil types, the urine N₂O EFs for those same five soil types ranged from 0.01% to 0.29% during the dry season and 0.12–1.36% during the wet season, which were attributed to differences in soil clay content and pH. Kelliher et al. (2014) also suggested disaggregating urine and dung N₂O EFs based on the terrain, as lower N₂O EFs were found under soils in terrain with slopes >12°. Although Van der Weerden et al. (2011) found inconclusive relationships between N₂O emissions and soil drainage class (well vs. poor) in New Zealand, they suggested that drainage classes should be considered when calculating national N₂O inventories due to the large variation in N₂O EFs across drainage classes. Unfortunately, most of the studies that estimated excreta N₂O EFs were only conducted on a single soil type, with many of these studies lacking basic soil information such

as clay content. In the future, experiments on diverse soils with specific soil descriptions are necessary to further reduce uncertainties in excreta N₂O EFs that can be used to improve national N₂O inventories.

4.3. Comparison with IPCC estimates and results from temperate regions

The IPCC 2019 refinement distinguishes between wet and dry climate but without separating tropical and temperate regions. However, excreta N₂O EFs are generally lower in tropical regions compared to temperate regions (Zhu et al., 2020b; Lessa et al., 2014). This may create a bias for overestimation of excreta N₂O emissions in tropical regions due to the limited number of available observations (9 studies for tropical versus 116 studies for temperate regions). Consistent with this, the mean N₂O EFs for cattle dung (0.14%) and cattle urine (0.48%) based on the 153 observations in our study were lower than the values of 0.28% (cattle dung) and 0.76% (cattle urine) reported by Cai and Akiyama (2016), which included only five studies from tropical regions. However, the values we found were consistent with the values given in the IPCC 2019 refinement. The two sheep excreta studies were both conducted under wet climate with the mean N₂O EFs for sheep urine (0.23% vs. 0.39%) lower, while the mean N₂O EFs for sheep dung (0.04% vs. 0.04) were in line with values for wet climate given in the IPCC 2019 refinement (Kristell et al., 2019).

However, we found that dung N₂O EFs in SSA were one magnitude lower than those reported for LAM, while urine N₂O EFs in SSA were 50% lower than in LAM, which might be due to differences in excreta chemistry (Bertram et al., 2009), soils (Zhu et al., 2020a), plant community (Simon et al., 2019) or climatic conditions (Chadwick et al., 2018). Based on the 14 studies from LAM and 6 studies from SSA, the IPCC 2019 refinement may be representative for certain tropical areas such as Australia and Brazil, however more data are needed for SSA as the EFs from excreta on pasture in SSA were inconsistent with other tropical areas and the IPCC refinement. In addition, studies investigating the effects of climate, soil, animal type (cattle vs. sheep) and excreta type (dung vs. urine) on N₂O EFs should be conducted in different production systems across SSA, ranging from pastoral low-input systems in arid and semi-arid areas to (relatively) high-intensity dairy systems in the more humid highlands.

5. Conclusion

Through our field study, we determined that the N₂O EFs for dung and urine patches from cattle deposited onto grasslands were not affected by dung mass or urine volume. In our synthesis of observations from tropical regions in SSA and LAM, we found that excreta N₂O EFs were in line with the values provided in the recent IPCC 2019 refinements. However, N₂O emissions from excreta patches in SSA may still be overestimated by the IPCC refinement as the EFs were substantially lower than those for LAM. In addition, the large variation among N₂O EFs highlights that to better estimate N₂O emissions from livestock excreta, other parameters (e.g. soils, vegetation, etc.) should also be considered. Finally, when determining national inventories of N₂O emissions from livestock excreta, it is crucial to include not only the disaggregated EFs for dung and urine, but also an appropriate measure of how N is partitioned between urine or dung as the proportion of N excreted appears to be quite different between SSA and other regions. This indicates that more studies are required in SSA that determine the relative proportions of N excreted as urine and dung and/or uses proxies to determine N excretion rates such as intake measurements, or live-weight gain measurements etc.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Daniel Korir as well as the other colleagues of the Mazingira Centre for all their help. Yuhao Zhu acknowledges the financial support from the China Scholarship Council (No. 201506350087) and MICMoR fellowship, Germany (KIT, IMK-IFU). Major funding was also provided by the Research Program ATM within the Earth and Environment Program of the German Helmholtz Association, Germany. The authors further acknowledge the CGIAR Fund Council, Australia (ACIAR), Irish Aid, European Union, International Fund for Agricultural Development (IFAD), Netherlands, New Zealand, UK, USAID and Thailand for funding to the CGIAR Research Program on Livestock.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2021.107637](https://doi.org/10.1016/j.agee.2021.107637).

References

- Barneze, A.S., Mazzetto, A.M., Zani, C.F., Misselbrook, T., Cerri, C.C., 2014. Nitrous oxide emissions from soil due to urine deposition by grazing cattle in Brazil. *Atmos. Environ.* 92, 394–397. <https://doi.org/10.1016/j.atmosenv.2014.04.046>.
- Bertram, J.E., Clough, T.J., Sherlock, R.R., Condron, L.M., O'Callaghan, M., Wells, N.S., Ray, J.L., 2009. Hippuric acid and benzoic acid inhibition of urine derived N₂O emissions from soil. *Glob. Change Biol.* 15, 2067–2077. <https://doi.org/10.1111/j.1365-2486.2008.01779.x>.
- Bretas, I.L., Paciullo, D.S.C., Alves, B.J.R., Martins, M.R., Cardoso, A.S., Lima, M.A., Rodrigues, R.A.R., Silva, F.F., Chizzotti, F.H.M., 2020. Nitrous oxide, methane, and ammonia emissions from cattle excreta on Brachiaria decumbens growing in monoculture or silvopasture with Acacia mangium and Eucalyptus grandis. *Agric. Ecosyst. Environ.* 295, 106896. <https://doi.org/10.1016/j.agee.2020.106896>.
- Butterbach-Bahl, K., Gasche, R., Breuer, L., Papen, H., 1997. Fluxes of NO and N₂O from temperate forest soils: impact of forest type, N deposition and of liming on the NO and N₂O emissions. *Nutr. Cycl. Agroecosyst.* 48, 79–90. <https://doi.org/10.1023/a:1009785521107>.
- Butterbach-Bahl, K., Gettel, G., Kiese, R., Fuchs, K., Werner, C., Rahimi, J., Barthel, M., Merbold, L., 2020. Livestock enclosures in drylands of Sub-Saharan Africa are overlooked hotspots of N₂O emissions. *Nat. Commun.* 11. <https://doi.org/10.1038/s41467-020-18359-y>.
- Byrnes, R.C., Nunez, J., Arenas, L., Rao, I., Trujillo, C., Alvarez, C., Arango, J., Rasche, F., Chirinda, N., 2017. Biological nitrification inhibition by Brachiaria grasses mitigates soil nitrous oxide emissions from bovine urine patches. *Soil Biol. Biochem.* 107, 156–163. <https://doi.org/10.1016/j.soilbio.2016.12.029>.
- Cai, Y., Akiyama, H., 2016. Nitrogen loss factors of nitrogen trace gas emissions and leaching from excreta patches in grassland ecosystems: a summary of available data. *Sci. Total Environ.* 572, 185–195. <https://doi.org/10.1016/j.scitotenv.2016.07.222>.
- Cai, Y., Chang, S.X., Cheng, Y., 2017. Greenhouse gas emissions from excreta patches of grazing animals and their mitigation strategies. *Earth-Sci. Rev.* 171, 44–57. <https://doi.org/10.1016/j.earscirev.2017.05.013>.
- Cardoso, A.D.S., Alves, B.J.R., Urquiaga, S., Boddey, R.M., 2018. Effect of volume of urine and mass of faeces on N₂O and CH₄ emissions of dairy-cow excreta in a tropical pasture. *Anim. Prod. Sci.* 58, 1079. <https://doi.org/10.1071/AN15392>.
- Cardoso, A. da S., Oliveira, S.C., Januszkiewicz, E.R., Brito, L.F., Morgado, E. da S., Reis, R.A., Ruggieri, A.C., 2019. Seasonal effects on ammonia, nitrous oxide, and methane emissions for beef cattle excreta and urea fertilizer applied to a tropical pasture. *Soil Tillage Res.* 194, 104341. <https://doi.org/10.1016/j.still.2019.104341>.
- Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G., Rees, R.M., 2018. The contribution of cattle urine and dung to nitrous oxide emissions: Quantification of country specific emission factors and implications for national inventories. *Sci. Total Environ.* 635, 607–617. <https://doi.org/10.1016/j.scitotenv.2018.04.152>.
- Chirinda, N., Loaiza, S., Arenas, L., Ruiz, V., Faverin, C., Alvarez, C., Savian, J.V., Belfon, R., Zuniga, K., Morales-Rincon, L.A., Trujillo, C., Arango, M., Rao, I., Arango, J., Peters, M., Barahona, R., Costa, C., Rosenstock, T.S., Richards, M., Martinez-Baron, D., Cardenas, L., 2019. Adequate vegetative cover decreases nitrous oxide emissions from cattle urine deposited in grazed pastures under rainy season conditions. *Sci. Rep.* 9, 1–9. <https://doi.org/10.1038/s41598-018-37453-2>.
- Dangal, S.R.S., Tian, H., Xu, R., Chang, J., Canadell, J.G., Ciais, P., Pan, S., Yang, J., Zhang, B., 2019. Global nitrous oxide emissions from pasturelands and rangelands: magnitude, spatiotemporal patterns, and attribution. *Glob. Biogeochem. Cycles* 33, 200–222. <https://doi.org/10.1029/2018GB006091>.
- de Bastos, D.F., Magiero, E.C., Tomazi, M., Schirmann, J., Veloso, M.G., de Faccio Carvalho, P.C., Bayer, C., 2020. A 3-year assessment of nitrous oxide emission factors for urine and dung of grazing sheep in a subtropical ecosystem. *J. Soils Sediment.* 20, 982–991. <https://doi.org/10.1007/s11368-019-02456-7>.

- Dijkstra, J., Oenema, O., van Groenigen, J.W., Spek, J.W., van Vuuren, A.M., Bannink, A., 2013. Diet effects on urine composition of cattle and N₂O emissions. *Animal* 7 (Suppl. 2), 292–302. <https://doi.org/10.1017/S1751731113000578>.
- IPCC, 2006. IPCC Guide-lines for National Greenhouse Gas Inventories. IPCC Geneva, Switzerland.
- Jones, S.K., Rees, R.M., Skiba, U.M., Ball, B.C., 2005. Greenhouse gas emissions from a managed grassland. *Glob. Planet. Change* 47, 201–211. <https://doi.org/10.1016/j.gloplacha.2004.10.011>.
- Kelliher, F.M., Cox, N., Van Der Weerden, T.J., De Klein, C.A.M., Luo, J., Cameron, K.C., Di, H.J., Giltrap, D., Rys, G., 2014. Statistical analysis of nitrous oxide emission factors from pastoral agriculture field trials conducted in New Zealand. *Environ. Pollut.* 186, 63–66. <https://doi.org/10.1016/j.envpol.2013.11.025>.
- Korir, D., Goopy, J.P., Gachui, C., Butterbach-Bahl, K., 2016. Supplementation with *Calliandra calothyrsus* improves nitrogen retention in cattle fed low-protein diets. *Anim. Prod. Sci.* 56, 619–626. <https://doi.org/10.1071/AN15569>.
- Kristell Hergoualc'h, Hiroko Akiyama, Martial Bernoux, Ngonidzashé Chirinda, Agustín del Prado, Ása Kasimir, James Douglas MacDonald, Stephen Michael Ogle, Kristiina Regina, T.J. van der W., 2019. N₂O emissions from managed soils, and CO₂ emissions from lime and urea application. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
- Lessa, A.C.R., Madari, B.E., Paredes, D.S., Boddey, R.M., Urquiaga, S., Jantalia, C.P., Alves, B.J.R., 2014. Bovine urine and dung deposited on Brazilian savannah pastures contribute differently to direct and indirect soil nitrous oxide emissions. *Agric. Ecosyst. Environ.* 190, 104–111. <https://doi.org/10.1016/j.agee.2014.01.010>.
- Marsden, K.A., Jones, D.L., Chadwick, D.R., 2016. The urine patch diffusional area: an important N₂O source? *Soil Biol. Biochem.* 92, 161–170. <https://doi.org/10.1016/j.soilbio.2015.10.011>.
- Mazzetto, A.M., Barneze, A.S., Feigl, B.J., Van Groenigen, J.W., Oenema, O., Cerri, C.C., 2014. Temperature and moisture affect methane and nitrous oxide emission from bovine manure patches in tropical conditions. *Soil Biol. Biochem.* 76, 242–248. <https://doi.org/10.1016/j.soilbio.2014.05.026>.
- Mazzetto, A.M., Barneze, A.S., Feigl, B.J., Van Groenigen, J.W., Oenema, O., De Klein, C.A.M., Cerri, C.C., 2015. Use of the nitrification inhibitor dicyandiamide (DCD) does not mitigate N₂O emission from bovine urine patches under Oxisol in Northwest Brazil. *Nutr. Cycl. Agroecosyst.* 101, 83–92. <https://doi.org/10.1007/s10705-014-9663-4>.
- Muturi, S.M., Muthui, L.W., Njogu, P.M., Onguso, J.M., Wachira, F.N., Opiyo, S.O., Pelle, R., 2021. Metagenomics survey unravels diversity of biogas microbiomes with potential to enhance productivity in Kenya. *PLoS One* 16, 0244755. <https://doi.org/10.1371/journal.pone.0244755>.
- Onyango, A.A., Dickhoefer, U., Rufino, M.C., Butterbach-Bahl, K., Goopy, J.P., 2019. Temporal and spatial variability in the nutritive value of pasture vegetation and supplement feedstuffs for domestic ruminants in Western Kenya. *Asian-Australas. J. Anim. Sci.* 32, 637–647. <https://doi.org/10.5713/ajas.18.0114>.
- Pelster, D.E., Gisore, B., Goopy, J., Korir, D., Koske, J.K., Rufino, M.C., Butterbach-Bahl, K., 2016. Methane and nitrous oxide emissions from cattle excreta on an east African grassland. *J. Environ. Qual.* 45, 1531–1539. <https://doi.org/10.2134/jeq2016.02.0050>.
- Rivera, J.E., Chará, J., Barahona, R., 2019. CH₄, CO₂ and N₂O emissions from grasslands and bovine excreta in two intensive tropical dairy production systems. *Agrofor. Syst.* 93, 915–928. <https://doi.org/10.1007/s10457-018-0187-9>.
- Rufino, M.C., Rowe, E.C., Delve, R.J., Giller, K.E., 2006. Nitrogen cycling efficiencies through resource-poor African crop-livestock systems. *Agric. Ecosyst. Environ.* 112, 261–282. <https://doi.org/10.1016/j.agee.2005.08.028>.
- Saarijärvi, K., Mattila, P.K., Virkajärvi, P., 2006. Ammonia volatilization from artificial dung and urine patches measured by the equilibrium concentration technique (JTI method). *Atmos. Environ.* 40, 5137–5145. <https://doi.org/10.1016/j.atmosenv.2006.03.052>.
- Selbie, D.R., Buckthought, L.E., Shepherd, M.A., 2015. The challenge of the urine patch for managing nitrogen in grazed pasture systems. *Adv. Agron.* 129 (129), 229–292. <https://doi.org/10.1016/bs.agron.2014.09.004>.
- Simon, P.L., Dieckow, J., de Klein, C.A.M., Zanatta, J.A., van der Weerden, T.J., Ramalho, B., Bayer, C., 2018. Nitrous oxide emission factors from cattle urine and dung, and dicyandiamide (DCD) as a mitigation strategy in subtropical pastures. *Agric. Ecosyst. Environ.* 267, 74–82. <https://doi.org/10.1016/j.agee.2018.08.013>.
- Simon, P.L., de Klein, C.A.M., Worth, W., Rutherford, A.J., Dieckow, J., 2019. The efficacy of *Plantago lanceolata* for mitigating nitrous oxide emissions from cattle urine patches. *Sci. Total Environ.* 691, 430–441. <https://doi.org/10.1016/j.scitotenv.2019.07.141>.
- Smith, J., Abegaz, A., Matthews, R.B., Subedi, M., Orskov, E.R., Tumwesige, V., Smith, P., 2014. What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa? *Biomass Bioenergy* 70, 58–72. <https://doi.org/10.1016/j.biombioe.2014.02.030>.
- Smith, P., Merbold, LutzVan Den Pol-van Dasselara, A., 2016. Role of European grasslands in the mitigation of climate change – potential, constraints and research challenges, in: The Multiple Roles of Grassland in the European Bioeconomy. In: Proceedings of the 26th General Meeting of the European Grassland Federation, Trondheim, Norway. NIBIO, pp. 730–745.
- Sordi, A., Dieckow, J., Bayer, C., Alburquerque, M.A., Piva, J.T., Zanatta, J.A., Tomazi, M., da Rosa, C.M., de Moraes, A., 2014. Nitrous oxide emission factors for urine and dung patches in a subtropical Brazilian pastureland. *Agric. Ecosyst. Environ.* 190, 94–103. <https://doi.org/10.1016/j.agee.2013.09.004>.
- Tian, H., Xu, R., Canadell, J.G., Thompson, R.L., Winiwarter, W., Suntharalingam, P., Davidson, E.A., Ciais, P., Jackson, R.B., Janssens-Maenhout, G., Prather, M.J., Regnier, P., Pan, N., Pan, S., Peters, G.P., Shi, H., Tubiello, F.N., Zaehle, S., Zhou, F., Arneeth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A.F., Buitenhuis, E.T., Chang, J., Chipperfield, M.P., Dangal, S.R.S., Dlugokencky, E., Elkins, J.W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos, F., Krummel, P.B., Landolfi, A., Laruelle, G.G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D.B., Olin, S., Patra, P.K., Prinn, R.G., Raymond, P.A., Ruiz, D.J., van der Werf, G.R., Vuichard, N., Wang, J., Weiss, R.F., Wells, K.C., Wilson, C., Yang, J., Yao, Y., 2020. A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* 586, 248–256. <https://doi.org/10.1038/s41586-020-2780-0>.
- Tomazi, M., Magiero, E.C., Assmann, J.M., Bagatini, T., Dieckow, J., Carvalho, P.C. de F., Bayer, C., 2015. Sheep excreta as source of nitrous oxide in ryegrass pasture in southern Brazil. *Rev. Bras. Ciênc. Solo* 39, 1498–1506. <https://doi.org/10.1590/01000683rbcsc20140497>.
- Tully, K.L., Abwanda, S., Thiong'o, M., Mutuo, P.M., Rosenstock, T.S., 2017. Nitrous oxide and methane fluxes from urine and dung deposited on Kenyan pastures. *J. Environ. Qual.* 46, 921–929. <https://doi.org/10.2134/jeq2017.01.0040>.
- Van Groenigen, J.W., Velthof, G.L., Van Der Bolt, F.J.E., Vos, A., Kuikman, P.J., 2005. Seasonal variation in N₂O emissions from urine patches: Effects of urine concentration, soil compaction and dung. *Plant Soil* 273, 15–27. <https://doi.org/10.1007/s11104-004-6261-2>.
- Wassie, S.E., Ali, A.I.M., Korir, D., Butterbach-Bahl, K., Goopy, J., Merbold, L., Schlecht, E., Dickhoefer, U., 2019. Effects of feed intake level on efficiency of microbial protein synthesis and nitrogen balance in Boran steers consuming tropical poor-quality forage. *Arch. Anim. Nutr.* 73, 140–157. <https://doi.org/10.1080/1745039X.2019.1572343>.
- Zhu, Y., Merbold, L., Pelster, D., Diaz-Pines, E., Wanyama, G.N., Butterbach-Bahl, K., 2018. Effect of dung quantity and quality on greenhouse gas fluxes from tropical pastures in Kenya. *Glob. Biogeochem. Cycles* 32, 1589–1604. <https://doi.org/10.1029/2018GB005949>.
- Zhu, Y., Merbold, L., Leitner, S., Xia, L., Pelster, D.E., Diaz-Pines, E., Abwanda, S., Mutuo, P.M., Butterbach-Bahl, K., 2020a. Influence of soil properties on N₂O and CO₂ emissions from excreta deposited on tropical pastures in Kenya. *Soil Biol. Biochem.* 140, 107636. <https://doi.org/10.1016/j.soilbio.2019.107636>.
- Zhu, Y., Merbold, L., Leitner, S., Wolf, B., Pelster, D., Goopy, J., Butterbach-bahl, K., 2020b. Interactive effects of dung deposited onto urine patches on greenhouse gas fluxes from tropical pastures in Kenya. *Sci. Total Environ.*, 143184. <https://doi.org/10.1016/j.scitotenv.2020.143184>.