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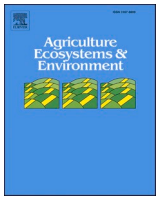

Greenhouse gas emissions from sheep excreta deposited onto tropical pastures in Kenya

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ABSTRACT

To improve the estimate of greenhouse gas emissions (GHG) from tropical rangelands in sub-Saharan Africa, we measured GHG emissions from sheep excreta over two periods of 51 days on a Kenya rangeland. In addition, we measured GHG emissions from potential hotspots in the landscape linked to sheep grazing: overnight enclosures ("bomas"), where sheep are kept at night to protect them from theft and predators, the areas surrounding sheep bomas, and areas surrounding watering troughs. Results showed a short pulse of CO_2 fluxes after sheep urine application and a rapid increase of CH_4 fluxes following sheep dung application in both rainy and dry season. However, only small increases of N_2O fluxes were observed after dung and urine applications compared to controls without excreta. Elevated N_2O fluxes mainly coincided with heavy rainfall. Overall, N_2O emission factors (EFs) did not vary across excreta type or seasons, but mean N_2O EFs for dung (0.01%) and urine patches (0.02%) were only one tenth of the default EFs from the 2019 IPCC Refinement for dry climate. We did, however, find that bomas and watering troughs are sites of herd concentration that are important sources of GHG emissions in the landscape, and that emissions in these locations can remain elevated for months to years, especially when soil moisture is high. This study contributes to more robust estimates of GHG emissions from African livestock systems, which are fundamental to develop targeted mitigation strategies.

1. Introduction

Grasslands occupy 40% of the world's terrestrial area (Hufkens et al., 2016; Parton et al., 2012) and a large fraction is used for livestock grazing (Zhou et al., 2018). Between 60% and 99% of the nutrients ingested by livestock are returned to the soil as excreta in the form of urine and dung that contain large amounts of nitrogen (N) and labile carbon (C), creating greenhouse gas (GHG) emission hotspots on grasslands, especially for nitrous oxide (N_2O) production (Cai et al., 2017; Haynes and Williams, 1993). In intensive cattle grazing systems, approximately 20% of the surface area is covered by urine annually (Moir et al., 2011) and ~5% is covered by dung (Ward et al., 2016). The amount of N contained in excreta patches by far exceeds plant N utilization, thus the surplus N contributes to N_2O loss (Chadwick et al., 2018). Globally, voided excreta on pasture are estimated to contribute 40% of total N_2O emissions from livestock production systems (Oenema et al., 2005). In addition to N_2O, excreta are a source of methane (CH_4): CH_4 from dung patches includes the release of enteric CH_4 embedded in the dung as well as newly produced CH_4 through methanogenesis after excretion (Maljanen et al., 2012). Previous research has shown that CH_4 emissions from dung patches may outweigh soil CH_4 uptake in tropical pastures (Zhu et al., 2021b). Furthermore, following urine deposition, urea hydrolysis and enhanced soil microbial respiration due to the addition of soluble C and water result in a pulse of carbon dioxide (CO_2) production (Boon et al., 2014). The addition of water, labile C, and gut microorganisms in fresh dung also increases soil CO_2 emissions (Zhu et al., 2020).

In sub-Saharan Africa (SSA), increasing livestock numbers and higher stocking rates are needed to meet the enhanced demand for livestock products of a growing population; subsequently GHG

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emissions from grazing land are likely to increase (Tian et al., 2020; Smith et al., 2016). Though excreta patches have been regarded as important GHG sources, according to our knowledge, there is no study that has measured GHG emissions from sheep excreta in sub-Saharan Africa. Most studies examining GHG emissions from excreta patches were conducted in temperate regions and have mainly focused on cattle. Cattle account for 77% of non-CO_2 emissions from the livestock sector (Herrero et al., 2013), more specifically 60% of the excreted N and N_2O emissions from animal production systems (Herrero et al., 2013; Van Groenigen et al., 2005). Because dung and urine behave very differently regarding their GHG emissions, the IPCC 2019 Refinement of the Guidelines for National Greenhouse Gas Inventories has provided disaggregated emission factors (EFs) for urine and dung for both cattle and sheep under wet and dry climates (Kristell et al., 2019). However, a series of recent studies showed that N_2O emissions from cattle dung and urine patches in tropical rangelands in SSA are up to 40% lower in comparison to the IPCC default EF of 0.24% (Kristell et al., 2019). This difference was found to be mainly due to low N concentrations in the excreta, which reflects the N-poor livestock diet (Zhu et al., 2020, 2018; Tully et al., 2017; Pelster et al., 2016). Therefore, it may be assumed that similar to cattle, also sheep fed with N-poor feed will have low excreta N concentrations and consequently N_2O emissions from sheep excreta patches will be lower than assumed by the IPCC. However, data points for sheep excreta included in the IPCC 2019 Refinement were extremely scarce, especially for dry climates. Furthermore, the N partitioning between urine and dung used by the IPCC 2019 Refinement was based on studies from cattle taken from a summary of trials in New Zealand (Kelliher et al., 2014). However, animal species, breed, and diet strongly influence N partitioning, resulting in large uncertainties when GHG emissions from excreta patches are assessed using default factors that do not represent local systems (Searle and Shipley, 2008).

Globally, the numbers of sheep are estimated at around 1.3 billion head in 2021 (FAO). Africa contains 27% of the global sheep population, which in arid and semi-arid lands (ASALs) are mainly fed on free grazing in the daytime (Butterbach-Bahl et al., 2020; Gilbert et al., 2018). Furthermore, in pastoral systems, livestock are typically held in overnight enclosures ("bomas" in Kiswahili, "kraals" in Afrikaans, "corrals" in English) to protect them from theft and predators. Manure in bomas is usually not used as fertilizer but left to accumulate over months or even years; consequently, bomas have been reported to be large but overlooked N_2O hotspots on the African continent (Butterbach-Bahl et al., 2020). To better assess GHG emissions from livestock excreta in tropical regions and reduce uncertainties in national and regional GHG budgets, the quantification of GHG emissions from bomas and excreta on pasture for different livestock species is urgently required.

To address this knowledge gap, we measured GHG emissions (i) from sheep dung and urine patches on a tropical grassland in Kenya, (ii) from sheep bomas, and (iii) from areas surrounding bomas and water troughs where sheep congregate during the day. We hypothesized that a) sheep dung patches are a small source of CH_4; b) both sheep urine and dung patches are N_2O sources, but due to the low feed quality in SSA N_2O EFs are lower than reported by the IPCC 2019 Refinement for dry climate; c) sheep bomas and areas surrounding bomas and water troughs are sources for N_2O and CH_4.

2. Materials and methods

2.1. Emissions from sheep excreta patches

We conducted a field experiment at the Mazingira Centre for Environmental Research and Education (https://mazingira.ilri.org/) of the International Livestock Research Institute (ILRI), Nairobi, Kenya (S 1°16'13"; E 36°43'23"; altitude 1809 m a.s.l.). The trial was set up on a grassland dominated by Kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.) and Rhodes grass (*Chloris gayana* Kunth), which was not grazed. The grass was cut to 5 cm by hand before the trial and every two to three weeks during the rainy season. The soils at our study site are well drained, deep humic nitisols based on the IUSS soil classification. The soil has a clay texture with a clay content of 62.7% (Zhu et al., 2021b). The topsoil (0–10 cm depth) contains 2.38 ± 0.00 g N kg^{-1}, and 23.3 ± 2.8 g C kg^{-1} and the soil pH measured in water (1:2.5) is 6.5 ± 0.1. The long-term mean annual precipitation at the site is 869 mm with a long rainy season from March to June and a short rainy season from October to December. The annual precipitation in 2022 when we conducted our measurements was below average with only 635 mm.

To determine excreta effects on soil GHG emissions, six treatments were included in the trial: control (no excreta application), 0.6 L distilled water, 0.6 L urine, 0.33 kg dung, 0.6 L water + 0.33 kg dung, and 0.6 L urine + 0.33 kg dung. Each treatment consisted of three spatial replicates. The application rate was based on a previous study from tropical regions in Brazil, which described the volume per urine patch (75 ml on an area of 31 cm^2) and the mass per dung patch (7 g fresh weight on an area of 15.5 cm^2) excreted by a sheep with 30 kg live weight (Tomazi et al., 2015). We scaled those values to the area covered by the GHG flux chamber (0.25 m^2), which resulted in an application rate of 0.6 L urine and an amount of 1.125 kg fresh weight of dung. However, as the sheep dung in our study was drier as compared to values reported in the study in Brazil (dung moisture 30% in our study vs 71% in Brazil) and consequently having a lower weight, we scaled the amount relative to the moisture content and reduced the total amount placed in a chamber to 0.33 kg. The first trial was conducted from 23-May to 12-Jul-2022 in the rainy season, while the second trial was conducted from 23-Aug to 12-Oct-2022 in the dry season. Sheep dung and urine used in both trials were collected from an ongoing animal trial at the Mazingira Centre. In this animal trial, sheep of the local Red Maasai breed were fed with 1 kg Rhodes grass hay (*Chloris gayana*) and supplemented with 400 g dry Calliandra (*Calliandra calothyrsus*). To enable separate collection of dung and urine, sheep were kept in metabolic crates overnight. Fresh dung and urine were collected in the morning from three animals and applied within one hour to minimize N losses from ammonia (NH_3) volatilization. Before application, excreta from the replicate animals were mixed to form one composite dung and one urine sample. Sheep dung and urine sample collected for the first trial in the morning on 23-May-2022 contained 16.9 g N kg^{-1} DM with 34.6% water content for dung and 4 g N L^{-1} for urine, while for the second trial, dung collected on 23-Aug-2022 contained 10.6 g N kg^{-1} DM with 28.0% water content, and urine N concentration was 3.0 g N L^{-1} (Table 1).

Table 1
Water content, carbon (C) and nitrogen (N) concentrations and C/N ratio of dung, and N concentrations of urine applied to grasslands in Kenya during rainy season and dry season trials.

Period	Season	Excreta type	Excreta properties			
			Water content (%)	C_{conc} (g C kg^{-1} DM)	N_{conc} (g N kg^{-1} DM or g N L^{-1})	C/N ratio
16-May-2022 – 12-Jul-2022	Rainy season	Dung	34.6 ± 1.0a	420.3 ± 4.2a	16.9 ± 0.9a	24.9 ± 1.0a
		Urine	–	–	3.4 ± 0.2 A	–
16-Aug-2022 – 12-Oct-2022	Dry season	Dung	28.0 ± 3.0b	415.2 ± 0.9a	10.6 ± 0.1b	39.4 ± 0.4a
		Urine	–	–	3.0 ± 0.1B	–

Note: Values are means ± standard deviation (n = 3). DM means dry matter. Different lowercase letters indicate significant differences between seasons within dung property, and different uppercase letters indicate significant differences between seasons within urine N concentrations ($P < 0.05$).

To measure soil GHG fluxes, an automated static chamber system consisting of 18 individual chambers (0.5 m x 0.5 m x 0.15 m) and an automated gas sampling system were used (Butterbach-Bahl et al., 1997). The chambers were divided into six blocks of three chambers each. Chambers were deployed in rows approximately 0.5 m apart from each other. Each block was closed and sampled for 45 min during which changes in the GHG mixing ratios of the headspace were monitored sequentially in 1-min intervals. Then, the chambers were opened, and the next block was closed and sampled, with a total measurement cycle of 277 min for all 6 blocks. The 18 chambers (6 treatments, 3 replicates) were randomly distributed across the study site. However, due to technical properties of our automatic GHG chamber system, these 18 chambers were arranged in 6 blocks of 3 chambers each. Therefore, our study is not completely randomized. We tested for a potential "block" effect in a linear mixed effects model using "block" as random factor but found no significant effect. The sampled gas was analyzed for CO_2, CH_4 and N_2O concentrations by a cavity ringdown laser absorption spectrometer (G2308, Picarro Inc., Santa Clara, CA, USA).

In both trials, dung, urine and/or water were applied directly into the GHG flux chambers at around 10 am, and GHG flux measurements were started immediately after application. GHG fluxes in both trials were monitored for 51 days after application when GHG fluxes in the treated plots had returned to background levels for a period of at least two weeks. After the first trial was completed, GHG flux chambers were moved to unaffected grassland to avoid legacy effects of the prior excreta residues. In the dry season, due to very dry conditions we simulated three small rainfall events (20, 30 and 30 mm), which are common in the dry season in the area, to stimulate GHG fluxes. The GHG fluxes were calculated using a linear regression approach and R^2 values of the linear regression on the increase/decrease of GHG concentrations in the closed chamber were used as decision criteria to keep or discard measurements (Yao et al., 2015). For all three gases, flux rates were discarded if the R^2 for CO_2 fluxes was < 0.8 as this could have indicated a leak in the measurement system. We did not remove CH_4 or N_2O fluxes with low R^2 values because in tropical grasslands, these gases typically have low flux rates (and hence a linear regression with a low R^2) for most of the time with exceptions after rainfall events that trigger short emission pulses (particularly for N_2O). Removing CH_4 or N_2O fluxes with a low R^2 would therefore lead to overestimation of cumulative emissions (Croghan and Egeghy, 2003). Of all fluxes measured, less than 6% of the CO_2, CH_4 and N_2O fluxes were finally discarded.

The EF was calculated as the percentage loss of added C or N over the length of the trials. For dung-only plots, the N_2O EF was calculated using the N_2O emissions from dung-only plots minus control plots, while for the urine-only and urine + dung plots, it was calculated by subtracting N_2O emissions from water-only plots to account for any soil rewetting effects on N_2O emissions. The resulting net excreta-induced N_2O emissions were then divided by the amount of N applied. The CH_4 EF was only calculated for dung using the cumulative CH_4 emissions from dung addition plots minus that from control plots and then dividing the dung-induced CH_4 emissions by total C application via dung. Urine was not regarded as an important source of CH_4 because it contains little C which is quickly lost as CO_2; therefore, no CH_4 EF was calculated.

Soil samples for mineral N analysis were taken at different depths (0–5 cm, 5–10 cm, and 10–20 cm) using a soil auger after excreta application at 5 times in the rainy season and 7 times in the dry season. Precipitation, air temperature and soil moisture at 5 cm depth were recorded with a weather station (ATMOS 41 weather station and TEROS-11 soil sensor, METER Environment, Munich, Germany) located directly next to the experiment.

2.2. GHG emissions from sheep bomas

To estimate GHG emissions from sheep bomas, we conducted measurements at ILRI's Kapiti Research Station & Wildlife Conservancy (S1°38'20"; E37°10'36"; altitude 1864 m a.s.l.), Machakos, Kenya. The Kapiti Station spans across 13,000 ha and is located in the semi-arid region of southern Kenya, with a mean annual precipitation of 550 mm. Sheep in Kapiti are of the local Red Maasai and Dorper breeds that are freely grazed on natural savanna grassland during daytime and enclosed in bomas during the night. Sheep bomas are relocated to a fresh spot every 3 days to reduce soil disturbance. In this study, we measured two bomas with a diameter of 17–19 m and manure layer less than 1 cm that housed 247 sheep:

- Boma I was established on 23-Apr-2023, abandoned on 26-Apr-2023, and GHG fluxes were measured six times between 25 April 2023 and 07-Jun-2023 (once in the active boma and 5 times in the abandoned boma).
- Boma II was established on 18-Apr-2023, abandoned on 21-Apr-2023, and GHG fluxes were measured six times between 25-Apr-2023 and 07-Jun-2023 in the abandoned boma.

Inside each boma, three points were randomly selected for gas flux measurements and soil and manure sampling. In addition to the boma measurements, we also measured GHG fluxes and took soil samples in the grazing area surrounding the bomas from three points each at distances of 5 m and 100 m from the boma fence. Furthermore, another three points were selected for GHG measurements in an area of 1 m surrounding watering troughs and measured at the same days as the boma points. The watering trough had dried when we went there the fourth time on 17-May-2023.

Concentrations of GHGs were detected using a Li-850 infra-red gas analyzer (LI-COR Biosciences, Lincoln, US) for CO_2 and an LGR-ICOS laser gas analyzer (Los Gatos Research, ABB, Zurich, Switzerland) for CH_4 and N_2O connected to a dark static chamber with a diameter of 30 cm. The GHG concentration change was measured for at least 5 min at each point.

2.3. Soil, urine and dung analysis

For both experiments (excreta on pasture and bomas), water content of sheep dung and boma manure was measured through oven-drying at 105 °C until constant weight. The total C and N for soil, sheep dung, and boma manure were analyzed with an elemental combustion system (VarioMAX Cube, Elementar, Langenselbold, Germany). The N concentration of sheep urine was analyzed via chemiluminescence on a total N analyzer for liquid samples (Shimadzu TNM-L, Duisburg, Germany). Ammonium (NH_4^+) and nitrate (NO_3^-) were extracted from soil and boma manure with 1 *M* KCl and then analyzed colorimetrically (Hood--Nowotny et al., 2010).

2.4. Data analysis

Differences between seasons in the properties (e.g., water content, C and N concentration and C/N ratio) of fresh dung, and urine N concentrations in each season were tested using a one-way ANOVA with Tukey's HSD test. Differences in cumulative CO_2, CH_4 and N_2O emissions and CH_4 and N_2O EFs across different treatments in both rainy and dry seasons were tested with a two-way ANOVA using treatment and season as fixed factors and block as a random factor. Testing for normal distribution using the Shapiro-Wilk test showed that all residuals were normally distributed. All statistical calculations were done in R 4.3.0 (R core team, 2023).

3. Results

3.1. GHG emissions from excreta patches

Mean CO_2 fluxes from control plots in the rainy season (32.7 mg CO_2-C m^2 h^{-1}) were half of those in the dry season (72.8 mg CO_2-C m^2 h^{-1}). While air temperatures (wet season air temperature 16.6 °C; dry season

air temperature 17.1 °C) and soil moisture (mean wet season: 24.2%; mean dry season: 23.4%) were similar in the dry and wet season, we believe that differences in cumulative CO_2 fluxes were mainly due to differences in plant biomass, which was higher in the dry season as indicated by a higher plant height. Consequently, higher soil CO_2 emissions might reflect higher rates of plant root respiration. Water addition did not increase CO_2 fluxes in the rainy season but increased them from 43.7 ± 3.1–65.3 ± 3.2 mg CO_2-C m^2 h^{-1} in the dry season (Fig. 2a). However, in both seasons, CO_2 fluxes increased rapidly after urine or urine + dung addition, with the highest observed peaks of 107.5 ± 14.0 mg CO_2-C m^2 h^{-1} from urine + dung application in the rainy season and 256.4 ± 116.9 mg CO_2-C m^2 h^{-1} from urine-only application in the dry season (Fig. 1a & 2a). Addition of dung-only increased CO_2 fluxes after 4 days in the rainy season, which coincided with a heavy rainfall event, while there was only a negligible effect of dung addition in the dry season. Despite some differences in CO_2 flux rates, cumulative CO_2 emissions over the experimental period (51 days) were not statistically significant among the different application treatments in each season ($P > 0.05$; Table 2 & 3).

In both seasons, the grassland soil acted as a small sink for atmospheric CH_4, with higher mean uptake rates in the rainy season (−3.72 μg CH_4-C m^2 h^{-1}) compared to the dry season (−0.58 μg CH_4-C m^2 h^{-1}). Water and urine addition had only marginal effects on CH_4 fluxes (Fig. 1b & 2b). After dung addition, CH_4 fluxes increased slightly and stayed elevated for 1–2 weeks. Specifically in dry season, CH_4 fluxes increased to 144.30 ± 50.38 μg CH_4-C m^2 h^{-1} after urine + dung addition after a 20 mm rainfall simulation and following rainfall events (Fig. 2b). Over the trial duration, the cumulative CH_4 emissions from dung-only did not outweigh soil CH_4 uptake in the rainy season, while the plots receiving dung and urine + dung became CH_4 sources during

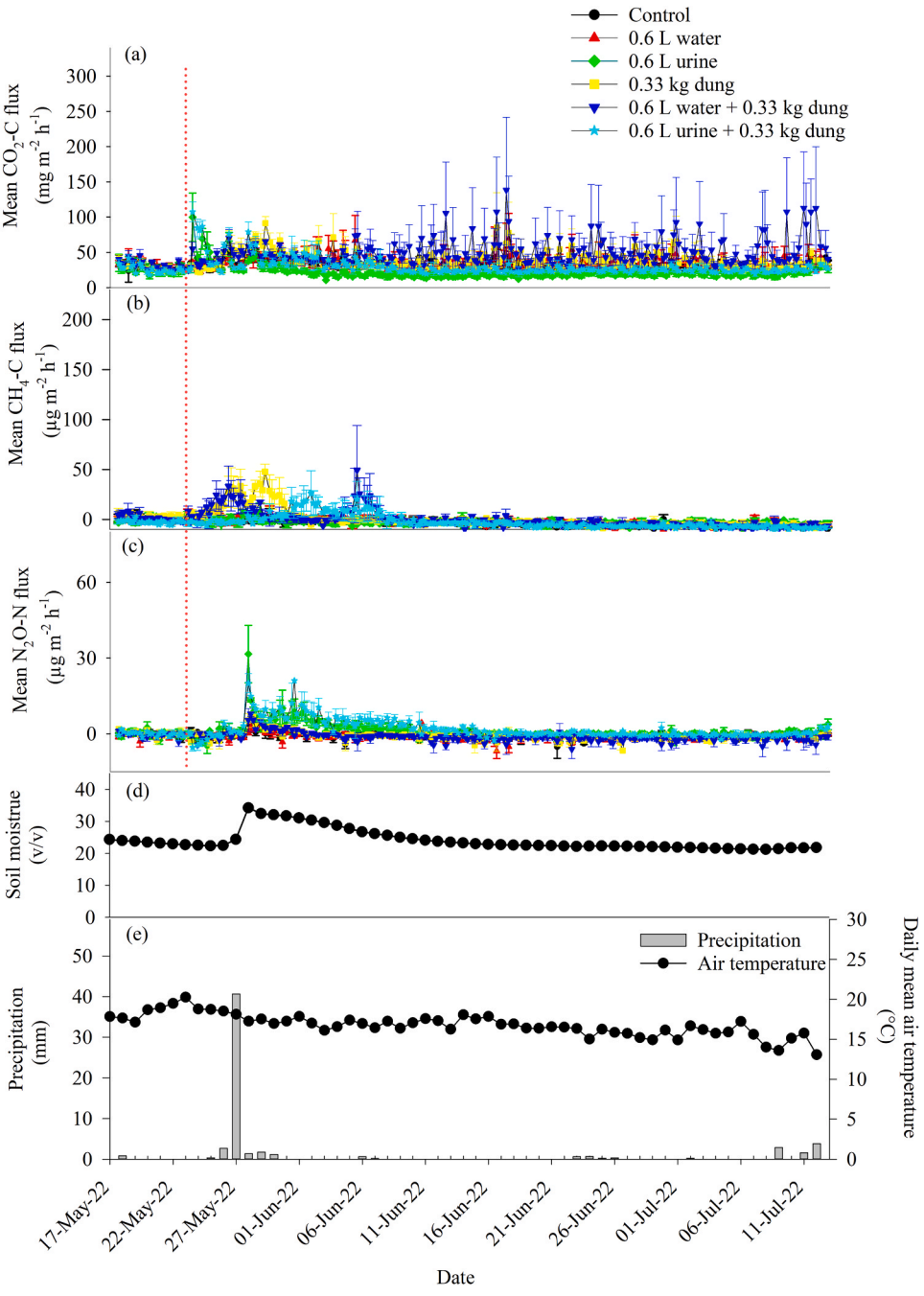

Fig. 1. Dynamics of (a) CO_2-C, (b) CH_4-C and (c) N_2O-N fluxes as affected by additions of different types of sheep excreta to grassland near Nairobi, Kenya during the rainy season (trial 1). The lower panels show the observed temporal dynamics of (d) mean daily soil moisture (0.05 m depth) and (e) air temperature and the daily sum of precipitation as observed at a climate station immediately adjacent to the study site. Each flux value represents the mean of three chambers (± SE), with fluxes being recorded in six hours' time intervals.

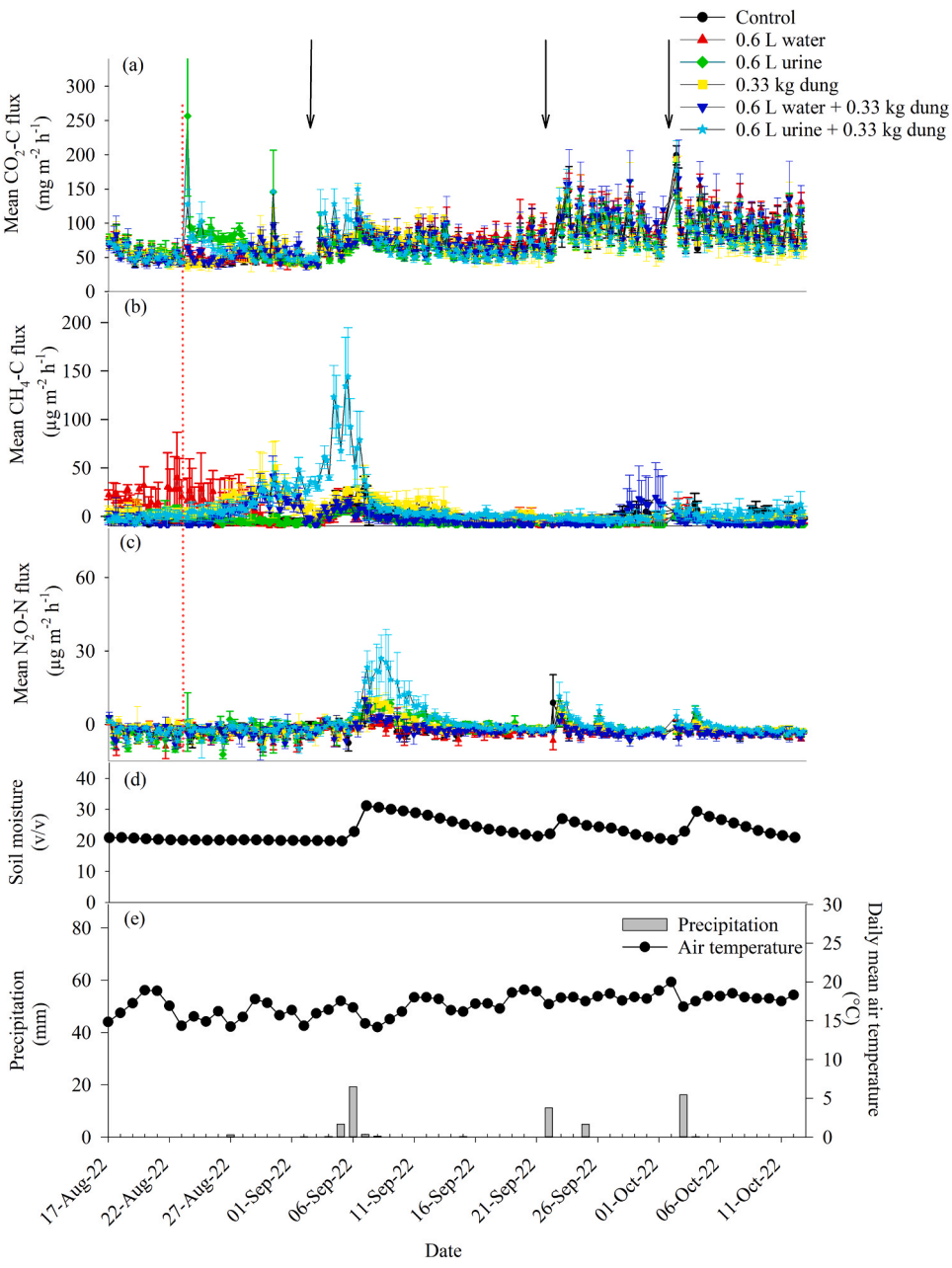

Fig. 2. Dynamics of (a) CO_2-C, (b) CH_4-C and (c) N_2O-N fluxes as affected by additions of different types of sheep excreta to grassland near Nairobi, Kenya during the dry season (trial 2). The lower panels show the observed temporal dynamics of (d) mean daily soil moisture (0.05 m depth) and (e) air temperature and the daily sum of precipitation as observed at a climate station immediately adjacent to the study site. Each flux value represents the mean of three chambers (± SE), with fluxes being recorded in six hours' time intervals. Dotted lines indicate the timing of application. The black rows indicate the simulated rainfall event of 20, 30 and 30 mm on September 3rd, September 22nd and October 2nd, respectively.

Table 2
Cumulative CO_2, CH_4 and N_2O emissions for sheep excreta applied to grassland in Kenya over a 51-d period from 23-May-2022–12-Jul-2022 (Trial 1 - rainy season).

Season	Treatment	N input by excreta (kg N ha^{-1})	Cumulative emissions		
			CO_2 (g CO_2-C m^{-2})	CH_4 (mg CH_4-C m^{-2})	N_2O (mg N_2O–N m^{-2})
Rainy season	Control, no application	0	39.6 ± 4.0	-4.7 ± 0.9	-0.9 ± 0.2
	0.6 L water	0	43.1 ± 14.9	-3.7 ± 1.4	-1.1 ± 0.5
	0.6 L urine	82.3	26.5 ± 6.8	-3.6 ± 1.3	1.2 ± 1.2
	0.33 kg dung	146.3	47.4 ± 12.4	-0.2 ± 2.1	-0.9 ± 0.2
	0.6 L water + 0.33 kg dung	146.3	60.8 ± 36.3	-0.4 ± 2.0	-1.4 ± 1.3
	0.6 L urine + 0.33 kg dung	228.5	36.4 ± 8.0	-2.7 ± 1.5	2.1 ± 1.7

Note: Values are mean ± standard deviation (n = 3). No significant difference among treatments in rainy could be found.

the dry season (Table 2 & 3). Nevertheless, the CH_4 EFs were small and similar across treatments, ranging from 0% to 0.004% in both seasons ($P > 0.05$; Table 4).

Background N_2O fluxes from the grassland soils in our study site were quite low, ranging from − 5.11–3.16 µg N_2O-N m^2 h^{-1}, with a mean of − 0.73 µg N_2O-N m^2 h^{-1} in the rainy season, and − 8.45–26.30 µg N_2O-N m^2 h^{-1}, with a mean of − 0.58 µg N_2O-N m^2 h^{-1} in the dry seasons. Surprisingly, neither urine nor dung application increased N_2O fluxes much in either of the seasons (Fig. 1c & 2c). An N_2O flux peak only occurred in plots receiving urine after a heavy

Table 3
Cumulative CO_2, CH_4 and N_2O emissions for excreta applied to grassland in Central Kenya over a 51 d period from 23-Aug-2022–12-Oct-2022 (Trial 2 - dry season).

Season	Treatment	N input by excreta (kg N ha^{-1})	Cumulative emissions		
			CO_2 (g CO_2-C m^{-2})	CH_4 (mg CH_4-C m^{-2})	N_2O (mg N_2O–N m^{-2})
Dry season	Control, no application	0	88.6 ± 20.6	-0.2 ± 2.9abc	-2.9 ± 1.6ab
	0.6 L water	0	99.3 ± 11.4	-2.7 ± 7.5bc	-3.2 ± 1.7b
	0.6 L urine	72.6	89.4 ± 12.4	-7.0 ± 2.3c	-1.3 ± 0.8ab
	0.33 kg dung	100.3	90.4 ± 32.1	7.8 ± 3.1ab	-1.5 ± 1.8ab
	0.6 L water + 0.33 kg dung	100.3	97.9 ± 28.5	-1.2 ± 10.6bc	-3.0 ± 1.8ab
	0.6 L urine + 0.33 kg dung	172.9	92.0 ± 19.9	13.5 ± 8.8a	1.1 ± 2.2a

Note: Values are mean ± standard deviation (n = 3). Different lowercase letters indicate significant differences within columns ($P < 0.05$).

Table 4
CH_4 and N_2O emission factors for excreta applied to grassland in Central Kenya during each of the two trials.

Treatment	EF_{CH4} (%)		EF_{N2O} (%)	
	Rainy season	Dry season	Rainy season	Dry season
0.6 L urine	–	–	0.020 ± 0.029	0.022 ± 0.016
0.33 kg dung	0.001 ± 0.001	0.002 ± 0.000	0.000 ± 0.002	0.014 ± 0.011
0.6 L water + 0.33 kg dung	0.001 ± 0.001	0.000 ± 0.003	-0.001 ± 0.009	0.002 ± 0.013
0.6 L urine + 0.33 kg dung	0.001 ± 0.001	0.004 ± 0.002	0.014 ± 0.005	0.025 ± 0.017

Note: Values are mean ± standard deviation (n = 3). Neither significant differences among trials within the same treatment nor significant differences among treatments within the same trial could be found ($P < 0.05$).

rainfall event (41 mm) four days after application, with the highest flux rates of 31.61 ± 11.36 μg N_2O-N m^2 h^{-1} in the dry season (Fig. 1c). In contrast, in plots receiving dung-only, fluxes increased only to 7.63 ± 0.08 μg N_2O-N m^2 h^{-1}. Similarly in the dry season, small N_2O flux peaks were observed coinciding with rainfall events, with the highest fluxes of 26.95 ± 9.56 μg N_2O-N m^2 h^{-1} measured in plots receiving urine + dung (Fig. 2c). Cumulative N_2O emissions were similar across treatments in the rainy season, while cumulative emissions from plots receiving urine + dung were higher than from water addition plots in the dry season ($P < 0.05$; Table 3). The N_2O EF did not differ across any of the urine and dung applications in either season, and no seasonal effect was found (Table 3). Overall, the N_2O EFs ranged from 0.000% to 0.025% (Table 4).

3.2. GHG emissions from sheep bomas

Soil moisture was highest at the first sampling time on 03-May-2023 (20–31%) and then decreased to < 10% for both bomas and soils (Fig. 3d).

Boma I had the highest CO_2 fluxes of 1011 ± 149 mg CO_2-C m^2 h^{-1} when it was active with lots of fresh urine and dung input (Fig. 3a). After the boma was abandoned, CO_2-C fluxes decreased rapidly and showed similar or even slightly lower CO_2 fluxes than surrounding areas that still had an intact plant cover (vegetation in the bomas was destroyed due to trampling and grazing).

Overall, soils from areas surrounding bomas at 5 m and 100 m distance were CH_4 sinks, with fluxes ranging from − 26.9 ± 2.3–10.7 ± 17.2 μg CH_4-C m^2 h^{-1}. In contrast, both bomas were significant CH_4 sources during our observation period, especially boma I when it was still in use, and showed the highest CH_4 flux of 688 ± 322 μg CH_4-C m^2 h^{-1} observed on 25-Apr-2023 (Fig. 3b). But even abandoned bomas had higher CH_4 fluxes (ranging from 16.4 ± 3.1–122 ± 89 μg CH_4-C m^2 h^{-1}) compared to surrounding soils. When the watering trough still had water on 25-Apr-2023, the CH_4 flux from soil 1 m away was 285 ± 261 μg CH_4-C m^2 h^{-1}. Afterwards, as the watering trough dried out, the soil was dry and CH_4 fluxes were low.

Both bomas acted as continuous N_2O sources during our observation period (Fig. 3c), with fluxes ranging from 39.9 ± 8.94–120 ± 64 μg N_2O-N m^2 h^{-1} (boma I) and 48.2 ± 11.4–2540 ± 1267 μg N_2O-N m^2 h^{-1} (boma II). In contrast, soil N_2O fluxes from surrounding areas were < 30 μg N_2O-N m^2 h^{-1} for both 5 and 100 m distance. Soil surrounding the watering trough emitted large amounts of N_2O (>500 μg N_2O-N m^2 h^{-1}) when the watering trough had water, but N_2O fluxes decreased to < 100 μg N_2O-N m^2 h^{-1} after the trough had dried out.

3.3. Soil mineral N dynamics in excreta patches and bomas

Background soil NH_4^+ concentration in control plots with no excreta addition was low and consistent at all three depths in our observation period in both seasons (<10 mg NH_4^+-N kg^{-1} soil DW). The highest soil NH_4^+ concentration (237 ± 23 mg NH_4^+-N kg^{-1} soil DW) was observed three days following urine + dung application in the rainy season (Fig. 4a). Soil NH_4^+ concentrations from urine and urine + dung applications at 5–10 cm depth, and urine and water + dung application at 10–20 cm depth were elevated three days after application (Fig. 4b & 4c). Stimulated by a rainfall event on 27-May-2022, soil NH_4^+ concentration at 0–5 cm depth reached 169.8 ± 8.6 (urine-only) and 30.7 ± 20.0 mg NH_4^+-N kg^{-1} soil DW (dung-only). Another small increase from water + dung treatment at 5–10 depth of 47.9 ± 12.2 mg NH_4^+-N kg^{-1} soil DW was also recorded (Fig. 4b). In contrast, soil NO_3^- concentrations were lower, ranging from 0.1 to 21.3 mg NO_3^--N kg^{-1} soil DW in all treatments at the three depths and did not vary much during our observation period (Figs. 4d, 4e & 4 f).

In the dry season, due to technical difficulties soil mineral N was sampled only from 9 days after excreta applications onwards. Nevertheless, soil NH_4^+ concentration was still elevated after urine application compared to controls at 64.6 ± 29.1, 81.1 ± 4.6 and 30.9 ± 21.3 mg NH_4^+-N kg^{-1} soil DW at 0–5, 5–10 and 10–20 cm depth, respectively (Figs. 5a, 5b & 5c). Soil NH_4^+ concentration after urine + dung application was also slightly higher than in control plots at 0–5 and 10–20 cm depth. The simulated rainfall event on 03-Sep-2022 led to a substantial increase in soil NH_4^+ concentration in the urine treatment at 0–5 cm depth with 152.7 ± 31.1 mg NH_4^+-N kg^{-1} soil DW. For comparison, soil NH_4^+ concentrations in control plots were < 20 mg NH_4^+-N kg^{-1} soil DW at all three depths throughout our observation period. Similar to the rainy season, most of soil NO_3^- concentrations were < 10 mg NO_3^--N kg^{-1} soil DW at 0–5 cm depth, while that at 5–10 and 10–20 cm depths was even less with < 6 mg NO_3^--N kg^{-1} soil DW (Figs. 5d, 5e & 5 f).

In the bomas, the manure layer contained large amounts of NH_4^+, with highest concentrations in the active boma (959 ± 241 mg NH_4^+-N kg^{-1} DW) that decreased to 30.6 ± 2.0 after boma abandonment for boma I, and 491 ± 132 (active) to 28.2 ± 1.32 mg NH_4^+-N kg^{-1} DW (abandoned) for boma II (Fig. 6a). In contrast, manure NO_3^- was an order of magnitude lower and did not change much for boma II, while it was slightly more variable for boma I, increasing from 10.7 ± 1.0–128 ± 4 mg NO_3^--N kg^{-1} DW, then decreased again to 17.5 ± 0.8 mg NO_3^--N kg^{-1} DW (Fig. 6d). Mineral N concentrations in surface soils below the

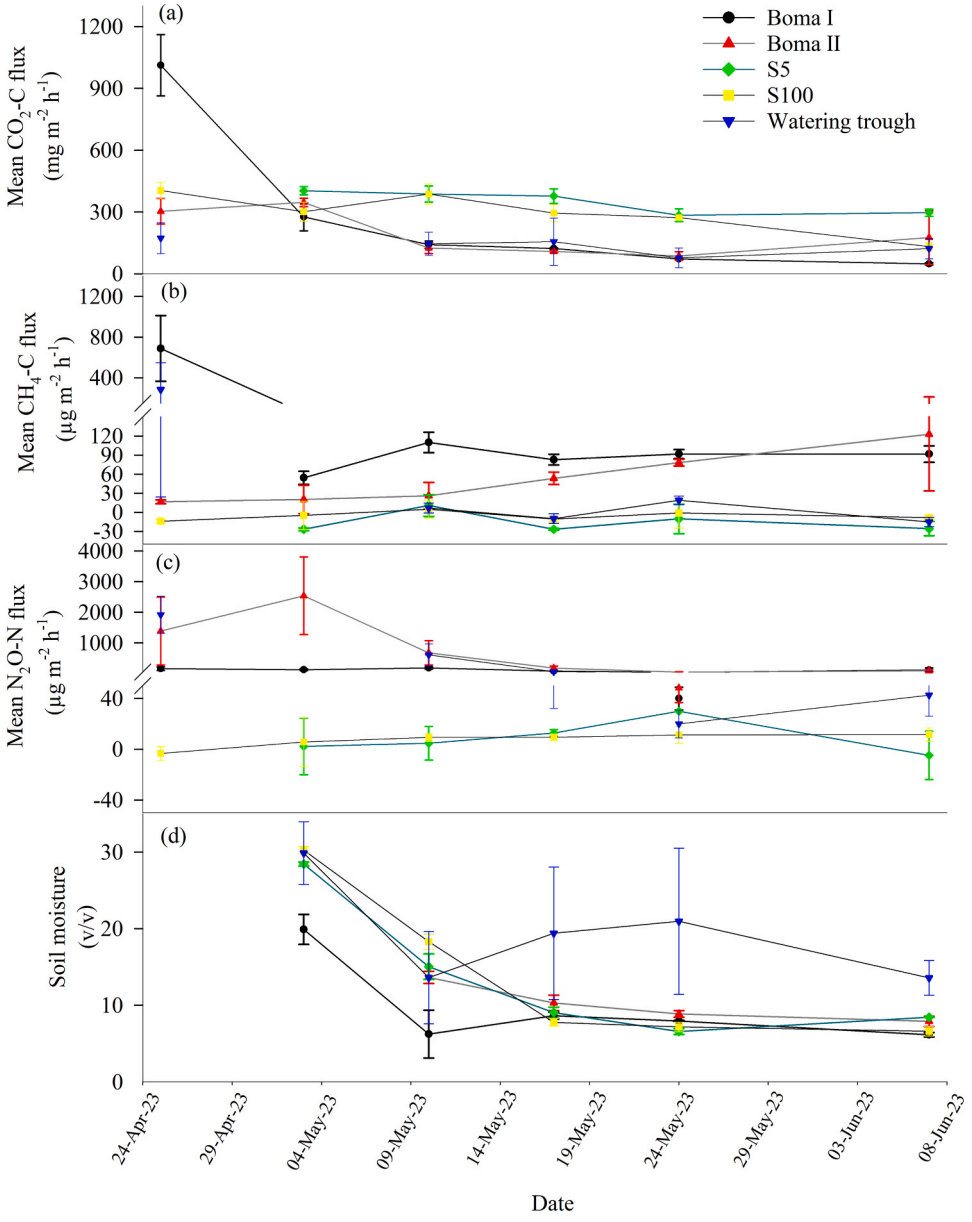

Fig. 3. Dynamics of (a) CO_2-C, (b) CH_4-C and (c) N_2O-N fluxes from Boma I, Boma II, surrounding areas (5 m and 100 m) and watering trough in Kapiti grassland, Kenya. The lower panels show the observed temporal dynamics of (d) mean daily soil moisture (0.05 m depth). Each flux value represents the mean of three chambers (± SE).

bomas were strongly influenced by the manure accumulation and showed higher NH_4^+ and NO_3^- concentrations than the surrounding soils at 5 m and 100 m distance (Fig. 6b & 6e), while there were no big differences in NH_4^+ concentrations in subsurface soils (<10 cm) for any of the sites (Fig. 6c & 6 f). The surface soil NO_3^- concentration from soil near the watering trough varied largely from 0.45 ± 0.11–190 ± 3 mg NO_3^--N kg^{-1} DW.

4. Discussion

4.1. Effect of excreta types on GHG emissions

In our study, sheep urine addition resulted in a short pulse of CO_2 fluxes, while dung or water addition had negligible effects on CO_2 fluxes. Similar results have been reported by Wang et al. (2013) after sheep urine and dung application to a steppe in China. The hydrolysis of urea following urine addition is the main CO_2 source (Cai et al., 2017). However, Ma et al. (2006) reported a rapid increase of CO_2 fluxes after sheep dung application in a grassland of Inner Mongolia in China while we observed only low CO_2 emissions from dung in our study. This may be attributed to the higher water content of the dung in their study compared to the dung we used in Kenya (65.2% vs 34.6% and 28% in our study), which might have promoted CO_2 emissions from microbial activity.

In partial agreement with our first hypothesis, dung addition did increase CH_4 fluxes in both rainy and dry seasons. Fresh dung from ruminants contains methanogenic microorganisms and large amounts of labile organic C, which promotes CH_4 formation (Nichols et al., 2016; Ho et al., 2015). However, the largest flux after dung application in our study was only 1440 µg CH_4-C m^2 h^{-1}, much lower than the peaks > 5000 µg CH_4-C m^2 h^{-1} observed after sheep dung application in a temperate grassland in China (Wang et al., 2013) In line with these low CH_4 fluxes, cumulative CH_4 emissions from sheep dung addition during our observation period were not different than emissions from control

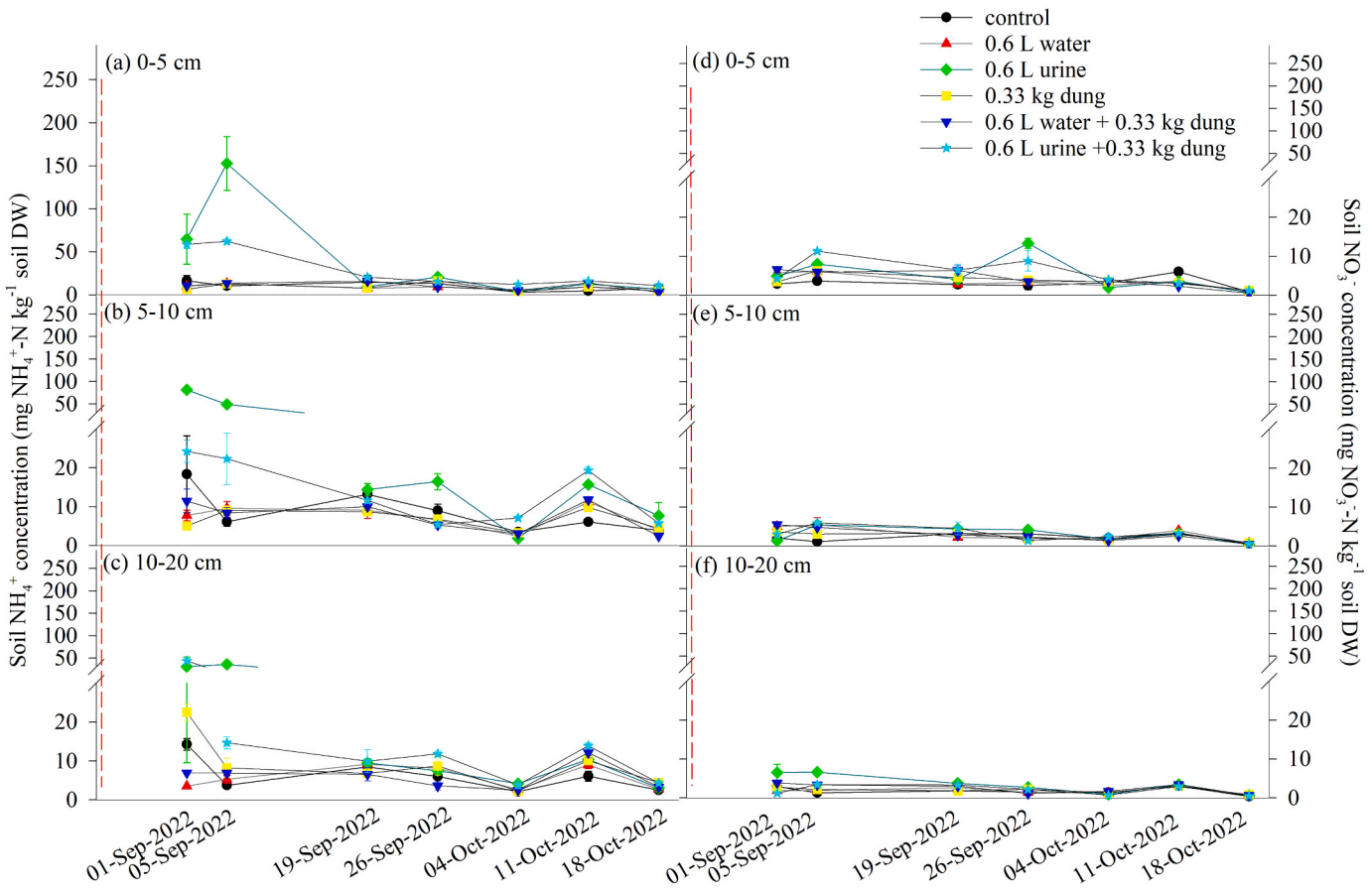

Fig. 4. Dynamics of soil NH_4^+ concentrations at (a) 0–5, (b) 5–10 and (c) 10–20 cm depth and soil NO_3^- concentrations at (d) 0–5, (e) 5–10 and (f) 10–20 cm depth as affected by additions of different types of sheep excreta to grassland in Nairobi, Kenya, during the rainy season. Dotted lines indicate the timing of application. Each data point represents the mean of three values (± SE).

plots, and the sheep dung CH_4 EF was one magnitude lower than what had been reported for cattle dung at the same site (Zhu et al., 2021b, 2018). Part of this might be explained by dung water content as we had found a strong positive correlation between CH_4 emissions and original dung water content in a previous study (Zhu et al., 2018). As expected, urine addition had minimal effects on soil CH_4 fluxes as urine addition does not affect the abundance of methanotrophs in the soil and only changes soil moisture minimally and transiently (Dai et al., 2013).

Contrary to our expectations (hypothesis ii), sheep dung addition only had a negligible effect on N_2O emissions. Zhu et al. (2018) had reported similar results from cattle dung application and ascribed it to the high dung C/N ratio as a result of the low-quality feed in Kenya. In addition, the low water content of the sheep dung and the hard pellet-like structure likely reduced the interaction between dung and soil and was not favorable for the mineralization of the organic N in the dung, which had been suggested to reduce N_2O emissions (Pelster et al., 2016). The sheep dung N_2O EF in our study ranged from 0% to 0.01%, which is one magnitude lower than the EF of 0.21% from IPCC 2019 Refinement for dry climate (Kristell et al., 2019). Similar to sheep dung, and even though sheep urine addition stimulated N_2O fluxes during the first days after application, fluxes rarely exceeded 30 μg N_2O-N m^2 h^{-1}, which was more than 10 times lower than fluxes reported in tropical Brazil under wet climate (de Bastos et al., 2020; Tomazi et al., 2015). Our study was conducted under dry climate following the IPCC definition (<1000 mm annual rainfall in tropics), but even so the sheep urine N_2O EF we obtained was by a magnitude lower than that of 0.31% for dry climate from IPCC 2019 Refinement (Kristell et al., 2019). We previously synthesized all studies conducted in tropics on N_2O emissions from excreta patches (Zhu et al., 2021a) and found that N_2O EFs were general lower under dry climate than wet climate for both cattle and sheep urine. Furthermore, the sheep urine-N and dung-N partitioning in the present study was 34:66 (Jesse Gakige, pers. comm.), which was close to that reported for cattle in Kenya (Rufino et al., 2006) but much lower than the default value used by the IPCC Refinement 2019 (Kristell et al., 2019). van der Weerden et al. (2021) also highlighted the importance of using different urine-N and dung-N partitioning for cattle (66:34) and sheep (35:65) to calculate overall excreta N_2O EF values. As urine generally has a higher N_2O EF than dung (Cai and Akiyama, 2016), using the IPCC default urine-N and dung-N portioning rate (which overestimates the urine proportion for African livestock) may overestimate N_2O emissions from excreta patches in SSA.

We nevertheless want to point out that our results might underestimate the N_2O EF due to the relatively dry year and the short observation period of our study. However, since our manual irrigation as well as the rainfall events we observed during the dry season did not stimulate large N_2O fluxes, we concluded that sheep excreta did not promote N_2O formation in the soil, most likely because of the low-N diet and consequently low N availability for denitrification. Previous studies in the same region showed that the N_2O EF for cattle dung was not influenced by seasons (Zhu et al., 2021b, 2018). Though the N_2O EF for cattle urine was highest in the short rainy season, it did not differ between long rainy season and dry season and the authors ascribed that to the urine N concentrations in different seasons (Zhu et al., 2021b). Our GHG measurement period in both seasons was 51 days, thus exceeding the requirements by IPCC of 30 days for the determination of EF for excreta deposited on rangelands (Kristell et al., 2019). Moreover, and rather commonly in these tropical grasslands, dung on the rangeland surface is removed by termites within days to weeks. In the present study, we

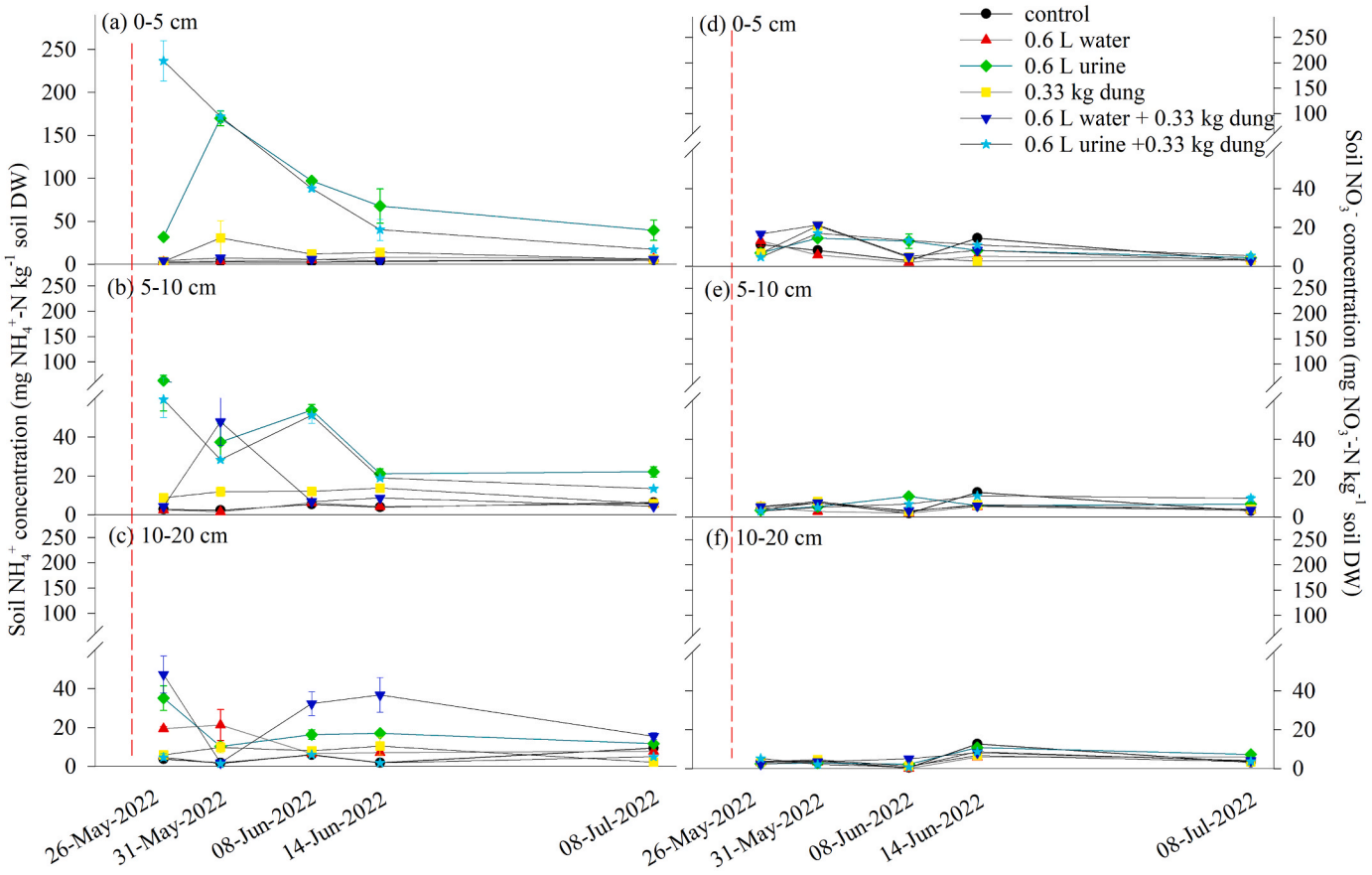

Fig. 5. Dynamics of NH_4^+ concentrations at (a) 0–5, (b) 5–10 and (c) 10–20 cm depth and NO_3^- concentrations at (d) 0–5, (e) 5–10 and (f) 10–20 cm depth as affected by additions of different types of sheep excreta to grassland in Nairobi, Kenya, during the dry season. Dotted lines indicate the timing of application. Each data point represents the mean of three values (± SE).

observed termites in the study plots within days after dung application, and no dung was visible on the surface anymore after four weeks in both the dry and rainy seasons.

4.2. Potential GHG emission hotspots in grazing lands

Herd concentration areas such as water troughs or laneways have been identified as GHG emission hotspots because of high local excretal input that results in elevated soil C and N contents (Mitchell et al., 2021). In agreement with this, bomas and watering trough area in our study were sources of CO_2, CH_4, and N_2O. Even though the sheep bomas only had a manure layer depth < 1 cm and dried out soon after abandonment, they remained large N_2O sources during our observation period. This is consistent with findings from others (Butterbach-Bahl et al., 2020) who reported that bomas in drylands of SSA are hotspots of N_2O emissions, and these emissions remain elevated for months to decades depending on the depth of the manure layer. Because we could not quantify the amount of manure that accumulated in bomas or was voided in the watering trough area, we could not calculate specific N_2O EFs for these locations. Future studies should quantify manure deposition rates and corresponding GHG emissions from herd concentration areas in tropical grasslands.

4.3. The dynamics of soil mineral N under excreta patches and bomas

Urine addition generally increases soil NH_4^+ concentration through urea hydrolysis (Bolan et al., 2004). Though urine addition also increased soil NH_4^+ concentration in our study, no N_2O pulse was observed. The NH_4^+ may have been lost in the form of NH_3 after urine application as soils were dry and air temperature was relatively high (17 °C), creating favorable conditions for NH_3 volatilization (Marsden et al., 2018). Another possible explanation is that mineral N was quickly immobilized by plants and microorganisms, as the grassland in our study site is N limited (Pelster et al., 2016). In contrast to urine, dung addition did not influence soil NH_4^+ concentration as the main N in the dung patch is in organic form and therefore takes time to be mineralized (Cai et al., 2017). Furthermore, the high C/N ratio of sheep dung due to the low-N diet potentially inhibited N mineralization, resulting in little release of NH_4^+ and NO_3^- into the soil (Zhu et al., 2018; Pelster et al., 2016).

In the grazing land on the Kapiti farm, we found that manure input increased soil NH_4^+ concentration, which is in line with other reported showing that more than 50% of urine-N can be stored in the soil at depth 0–15 cm in a grazing system in the UK (Reay et al., 2023). Since NH_4^+ input also promotes nitrification, NO_3^- concentration increases in soils with high NH_4^+ concentrations, which explains why the surface soil beneath sheep bomas also contained more NO_3^- than surrounding soils in our study.

5. Conclusion

Our study revealed that differences of N_2O and CH_4 emissions following sheep excreta application on a tropical rangeland were low, and N_2O and CH_4 EFs were not affected by excreta type (dung, urine, and their combination) or season (rainy versus dry season). Most importantly, our study shows that the default EF value of the IPCC 2019 Refinement for N_2O emissions from sheep excreta under dry climate conditions of 0.21% (sheep dung) and 0.31% (sheep urine) seems to be a significant overestimation as for both excreta types we found mean N_2O

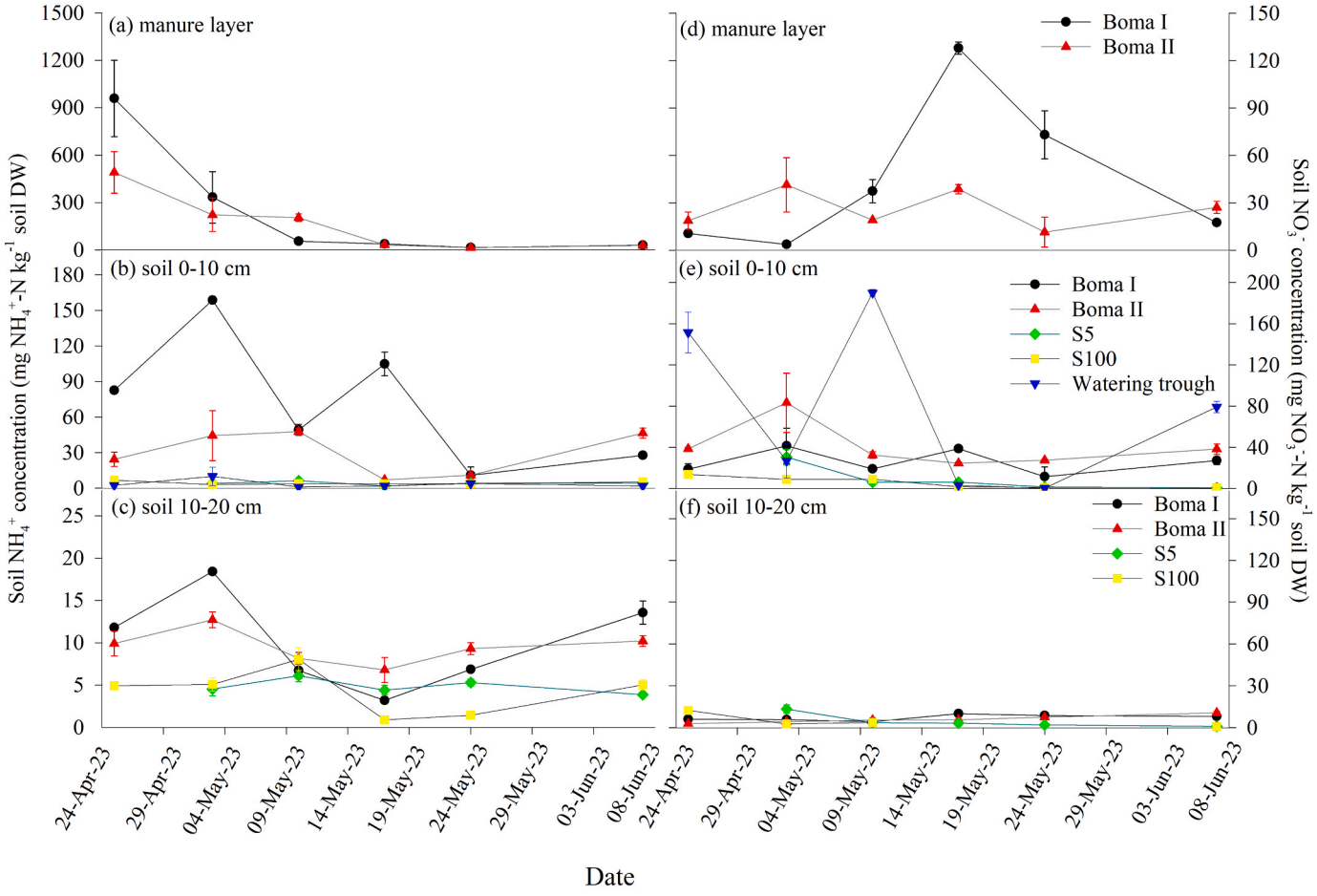

Fig. 6. Dynamics of NH_4^+ concentration at (a) manure layer, (b) 0–10 and (c) 10–20 cm depth and NO_3 concentration at (d) manure layer, (e) 0–10 and (f) 10–20 cm depth from Boma I, Boma II, areas surrounding bomas (at 5 m and 100 m distance) and watering troughs in the Kapiti grassland, Machakos, Kenya. Each data point represents the mean of three values (± SE).

EFs of ≤ 0.02%. This indicates that sheep excreta patches in tropical rangeland in SSA may be less important GHG sources as currently assumed. This effect is likely due to the low N concentration of the excreta and the low water content in the dung because local sheep breeds are generally more efficient in retaining water, and feeds are low in N. On the other hand, we found that GHG emissions from confinements and areas where sheep gather (such as water troughs) are overlooked sources of GHG emissions that are currently not accounted for in GHG inventories of African nations. Quantifying GHG emissions from such areas and developing local GHG EFs is critical for countries to move to Tier 2 reporting and develop mitigation strategies supporting low-emissions development.

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.

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