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Greenhouse gas emissions from cattle enclosures in semi-arid sub-Saharan Africa: The case of a rangeland in South-Central Kenya

Sonja Maria Leitner[a,*,1], Victoria Carbonell[a,b,c,1], Rangarirayi Lucia Mhindu[a,d], Yuhao Zhu[a], Paul Mutuo[a], Klaus Butterbach-Bahl[c,e], Lutz Merbold[f]

[a] International Livestock Research Institute (ILRI), Mazingira Centre for Environmental Research and Education, PO Box 30709, Nairobi, Kenya
[b] ETH Zurich, Department of Environmental System Sciences, Institute of Agricultural Sciences, Universitaetsstrasse 2, Zurich 8092, Switzerland
[c] Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Garmisch-Partenkirchen, Germany
[d] Midlands State University, Department for Land and Water Resources Management, P Bag 9055, Gweru, Zimbabwe
[e] Pioneer Center Land-CRAFT, Department of Agroecology, University of Aarhus, Aarhus, Denmark
[f] Agroscope, Research Division Agroecology and Environment, Integrative Agroecology Group, Reckenholzstrasse 191, Zurich 8046, Switzerland

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ABSTRACT

Extensive livestock production in pastoral areas supports millions of livestock keepers in Sub-Saharan Africa (SSA). However, it is also linked to environmental externalities such as greenhouse gas (GHG) emissions. Corralling of livestock overnight in fenced enclosures ("bomas" in Kiswahili) is common to protect animals from theft and predation and is practiced across SSA. Boma manure is usually not removed and accumulates over years, making bomas GHG emission hotspots. The following study presents the first full year of CO_2, CH_4, and N_2O emissions measurements from cattle bomas in a savanna ecosystem in Kenya, comparing active (in use) and inactive (i.e., abandoned) bomas. Active bomas were used for 1–3 months before being abandoned and cattle were moved to a new boma. GHG emissions were measured using static chambers inside three replicate bomas and along three 100 m transects from bomas into undisturbed savanna. Compared to savanna background fluxes, it was found that GHG flux rates from bomas were elevated by several orders of magnitude, with mean fluxes of 487 ± 8 mg CO_2-C m^{-2} h^{-1}, 325 ± 11 µg N_2O-N m^{-2} h^{-1}, and 3245 ± 234 µg CH_4-C m^{-2} h^{-1} for active bomas, and 167 ± 52 mg CO_2-C m^{-2} h^{-1}, 610 ± 186 µg N_2O-N m^{-2} h^{-1}, and 3127 ± 1262 µg CH_4-C m^{-2} h^{-1} for inactive bomas, while surrounding savanna soils only emitted 22.3 ± 18.2 mg CO_2-C m^{-2} h^{-1}, 2.5 ± 2.2 µg N_2O-N m^{-2} h^{-1}, and 0.1 ± 0.7 µg CH_4-C m^{-2} h^{-1}. Assuming that bomas are used for 45 days per year, annual manure emission factors were 2.43 ± 0.42%N for N_2O and 0.49 ± 0.07%C for CH_4, which corresponds to 2.64 ± 0.37 g CH_4 kg^{-1} volatile solids (VS). These emission factors were similar to IPCC default values for feedlots for low-producing cattle in warm climates; however, the IPCC only considers emissions in year when bomas are in use and does not account for emissions following boma abandonment. At the farm scale, boma manure contributed little (2.2%) to total CH_4 emissions, which were dominated by enteric CH_4 emissions (97.6%); but bomas were a substantial source for N_2O, contributing over 32% to total N_2O emissions on the farm. This calls for the inclusion of active and inactive bomas in the activity data collection for national GHG inventories, as bomas are currently overlooked hotspots for GHG emissions that are not represented in the GHG budgets of African nations. To mitigate GHG emissions, manure should be removed regularly and used as fertilizer to return nutrients to the grassland, preventing nutrient mining and ensuring long-term rangeland productivity and resilience, or it might be used to grow crops and livestock feeds.

* Corresponding author.
E-mail address: s.leitner@cgiar.org (S.M. Leitner).
[1] These authors should be considered joint first author

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1. Introduction

Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) are atmospheric greenhouse gases (GHGs) that cause rising global surface air temperatures as their atmospheric concentrations increase. In 2019, the agriculture, forestry, and other land use (AFOLU) sector contributed 21% (8.4 Gt C) to CO_2 emissions, 53% (195 Mt CH_4) to CH_4 emissions (FAO, 2021), and 52% (3.8 Tg N_2O-N) to N_2O emissions globally (Tian et al., 2020, FAO, 2020).

In many developing countries, the livestock sector is the major source of anthropogenic GHG emissions, most of which originate from enteric fermentation (39%) and manure emissions (26%) (FAO, 2020; Herrero et al., 2013). In 2018, Africa contributed 24% of global agricultural emissions. a contribution that is projected to increase (FAO, 2020). However, these estimates are largely based on modelling and upscaling of limited field- and laboratory-based observations, as measurements of GHG emissions from livestock systems in developing countries, particularly in Sub-Saharan Africa (SSA), are scarce (Graham et al., 2022). As a result, there is significant uncertainty in the accuracy of these estimates, which is particularly critical as Africa has the fastest growth rates in livestock numbers globally (Latino et al., 2020; Thornton, 2010).

This knowledge gap can be addressed by performing *in situ* GHG emission measurements that capture the diversity of livestock management practices in the region. In SSA, herding of ruminant livestock (e.g., cattle, sheep, goats) is often the primary source of income for rural societies (Barrett et al., 2003). In arid and semi-arid lands (ASALs), where the climate is less suitable for crops, pastoralism is the dominant livestock system and is practiced across ca. 40% of Africa's terrestrial area (ILRI et al., 2021). In SSA, 25 million pastoralists and 250 million agropastoralists depend on livestock as their primary source of income (MacCarthy, 2000). In such pastoral livestock systems, cattle typically graze during the day and are taken to water points to drink in the morning and afternoon, followed by being grouped overnight in permanent or semi-permanent enclosures (*boma* in Swahili; *kraal* in Afrikaans; *corrals* in English). The accumulation of large quantities of manure in such bomas renders them GHG emission hotspots with the potential to contribute largely to total non-CO_2 GHG emissions in pastoral systems (Butterbach-Bahl et al., 2020; Carbonell et al., 2021; Mgalula et al., 2021). Although there are some studies on GHG emissions from livestock manure in SSA (Brümmer et al., 2008; Leitner et al., 2021; Pelster et al., 2016; Zhu et al., 2021b, 2020b, 2018), to our knowledge only two have included *in situ* measurements of GHG emissions from bomas in SSA (Butterbach-Bahl et al., 2020; Zhu et al., 2024). Neither of these studies measured emissions for more than short field campaigns. Until such point sources of GHG emissions in SSA pastoral livestock systems have been thoroughly quantified, proper estimation of regional or national GHG budgets, and consequently the implementation of proper climate change mitigation strategies, will be challenging and incomplete.

Furthermore, the IPCC currently does not include bomas as a manure management system in its Guidelines for National GHG Inventories, nor does it include N_2O emissions from inactive livestock enclosures after abandonment (IPCC, 2019, 2006). The manure management category in the IPCC system that most resembles bomas is feedlots. However, feedlots are primarily found in industrialized livestock systems with improved, high-producing, cattle breeds fed on nutrient-dense feeds for fattening and finishing, and where manure is removed regularly from the animal enclosure. In addition, emissions from feedlots are only considered for the year in which the enclosures are in use and not for subsequent years after abandonment, when they may no longer be in use. In contrast, pastoral systems in SSA are characterized by small indigenous cattle breeds (e.g., Zebu, Boran, Sanga) (Mwai et al., 2015) as well as poor feed quality and seasonal feed scarcity (Goopy et al., 2018; Ndung'u et al., 2018). In addition, manure from bomas in remote areas not connected to crop production is rarely removed but accumulates in the boma and is left to decompose when the herd moves on and the boma is abandoned. Consequently, bomas are N_2O emission hotspots for years to decades that are estimated to contribute ca. 5% of the total anthropogenic N_2O emissions on the African continent (Butterbach-Bahl et al., 2020). Given the large number of cattle in pastoral systems (estimated 3 Mio. in Kenyan rangelands) (Ogutu et al., 2016), precise GHG emission factors for bomas are urgently needed to account for these emissions in national GHG inventories of African nations. To address this knowledge gap, we observed GHG emissions from active and inactive bomas and surrounding savanna in an East African rangeland system for the duration of one full year covering two dry and two wet seasons.

CO_2 in manure is produced by microbial respiration, and emissions are controlled by C and N availability and environmental conditions (temperature, moisture). CH_4 emissions from manure are controlled by moisture (which regulates O_2 availability), temperature, and C and N availability. During manure storage, CH_4 emissions are usually high immediately after excretion, then decrease (Zhu et al., 2021b), and only increase again if continuously anoxic conditions prevail. For example, inside the moist core of a manure heap (Chadwick, 2005), or in a slurry tank.

N_2O is produced through several N transformation processes (Butterbach-Bahl et al., 2013), with nitrification and denitrification considered as dominant sources of N_2O in livestock manure (Chadwick et al., 2011; Maeda et al., 2010). Manure N_2O emissions are highest under moist but not completely water-saturated conditions (Aguilar et al., 2014). Furthermore, N_2O emissions from manure are usually highest after a time lag of few days (Petersen et al., 2004; Zhu et al., 2021b) to several weeks (Leitner et al., 2021) after excretion because fresh manure (a mix of dung and urine) contains primarily NH_4^+ from urine and organic N from dung, which first need to be broken down and converted to NO_3^- before they can be denitrified to N_2O.

In addition to emissions originating directly from the manure, manure deposition also influences soil GHG emissions (Zhu et al., 2020b). Cattle congregate around the boma before being confined at night and after being released in the morning. During that time, they drop their faeces in the vicinity of the boma, which provides input of C, N and moisture from urine to soil microorganisms, thereby promoting CO_2 and N_2O emissions. Zhu et al. (2024) reported an increase in GHG emissions in the vicinity of sheep bomas compared to background savanna emissions in Kenya. In addition, fresh dung contains entrapped enteric CH_4 and viable methanogens, which leads to short-lived CH_4 pulses after dung deposition on grasslands (Zhu et al., 2021b, 2018). Consequently, it can be expected that GHG emissions around cattle bomas will be elevated compared to savanna background fluxes. However, the range of influence with increasing distance to bomas as well as effects of seasonality on GHG emissions remain to be quantified.

To address this lack of data and understand the underlying mechanisms, GHG flux data from cattle bomas and the savanna soils surrounding them were collected on a pastoral ranch in south-central Kenya over the course of one year. The specific objectives of the study were *i)* to quantify soil and manure GHG emissions from cattle bomas and adjacent soils in a grazed savanna landscape, and *ii)* to analyse temporal variation of boma and savanna soil GHG fluxes due to rainfall seasonality and seasonal mobility of cattle herds. Our hypotheses were (i) that bomas are a major N_2O emission source at the landscape scale, and that peak N_2O emissions occur a few weeks after boma abandonment, when urinary-N has been converted to NO_3^- and is fuelling denitrification, as well as for short periods after rainfall events, (ii) that CH_4 emissions from bomas are highest in fresh manure immediately after excretion, when methanogens from the rumen are still viable, as well as during the rainy season, when the manure layer is wet for an extended period, (iii) that CO_2 emissions are higher in bomas than adjacent savanna soils due to manure C input and increased microbial activity, and (iv) that savanna soil GHG emissions are elevated in the vicinity (up to 30 m) of bomas due to manure C and N input.

2. Materials and methods

2.1. Experimental site and boma management

This study was conducted at the Kapiti Research Station and Wildlife Conservancy (1°37'06.14''S, 37°06'09.02''E) of the International Livestock Research Institute (ILRI). This 14,000-ha farm is located in a semi-arid region in south-central Kenya, ca. 70 km south from the capital Nairobi (Carbonell et al., 2021). The climate is typical for semi-arid savannas, with precipitation below potential evapotranspiration. The mean annual precipitation is 550 mm, with rainfall being distributed in a bimodal precipitation regime (March-May and November-December). Approx. 80% of the annual precipitation occurs during these two periods. The mean annual temperature is 20.2°C, with 4°C of annual variation and substantial day and night variability. The soils in the study area are Salid Sodic Pellic Vertisols (Magnesic), locally known as "black cotton soils" (Charles K. K. Gachene, pers. comm.). The study area is dominated by savanna grasses (e.g., *Themeda triandra, Panicum spp., Chloris virgata*), with very few dispersed trees (e.g., *Vachellia* and *Senegalia* genera) and shrubs (e.g., *Euphorbia spp.* and *Hibiscus spp.*) (Muthoka et al., 2022).

Livestock management on the farm is representative for pastoral livestock production systems, where herders graze animals during the day and enclose them in corrals (bomas) during the night. During the time of the study, three herds of Boran cattle (*Bos indicus*) of 95–170 animals per herd were enclosed in three separate bomas ca. 5 – 10 m apart from 6 pm to 8 am (Fig. 1). The area where the bomas were located (1°36'7.42"S, 37° 7'52.54"E) is usually used for grazing for a few months every year, until cattle are moved to another area of the farm when the pasture in the area around the bomas is exhausted. While cattle were present, the position of the three bomas was moved by 10 – 30 m to an undisturbed area every 4–12 weeks and more frequently after heavy rains. This is a common practice in African pastoral systems where herders follow rainfall and pasture availability to allow the rangeland to rest and vegetation to regrow. During the duration of this study, the time during which bomas were actively used ranged from 26 days (Boma IV) to 85 days (Boma I) and was on average 45 ± 11 days (Table 1). The number of cattle per boma ranged from 95–170 head (mean 140 ± 6 head).

2.2. Sampling design

To cover temporal variation of GHG fluxes from bomas and savanna soils around the bomas, gas samples were collected at least weekly from November 2016 to December 2017, for a total of 67 sampling days. During this period, cattle were present in the study area from November 2016 until June 2017 and from October until December 2017. During the 2017 long dry season (June-October), cattle were moved to a different area of the farm, outside the study area (Table 1) to allow resting of the rangeland around the bomas.

The study area (250 m x 250 m) consisted of three replicates of moving bomas and the savanna soil around the bomas (Fig. 1). To capture GHG fluxes during and after active boma use, three GHG sampling points were set in each boma (Fig. 2), with each sampling point consisting of three chambers for gas pooling (see details in Section 2.3 below), giving a total of 9 sampling points with 27 chambers inside bomas. To capture background soil GHG fluxes and identify the extent of boma influence, samples were collected in the surrounding savanna along three transects of five sampling points (in the centre of the boma cluster, and at 5 m, 15 m, and 30 m from the boma fence of the first boma position of the study, see Fig. 2). On 28-Jun-2017, additional transect points were added at 100 m from the boma fence to include more undisturbed savanna locations, as the transect points at 30 m distance showed signs of frequent cattle presence (e.g., dung droppings, vegetation bite marks). Each sampling point along the savanna transects consisted of three chambers for gas pooling (see details on GHG sampling in the next section), giving a total of 15 fixed sampling points with 45 chambers in the savanna (Fig. 2). The sampling points along the savanna transects were kept at the same position throughout the entire year of measurements, whereas the boma positions were moved four times by 10 – 30 m to a new spot between November 2016 and June 2017 until the herders abandoned the area (Fig. S1). Following the movement of the bomas, the sampling points inside the bomas were changed accordingly:

- Boma position I: 09-Nov-2016–01-Feb-2017
- Boma position II: 01-Feb-2017–15-Mar-2017
- Boma position III: 15-Mar-2017–28-Apr-2017
- Boma position IV: 28-Apr-2017–25-May-2017
- Boma position V: 25-May-2017–20-Jun-2017

Measurements continued in the study area along the transects and at Boma position V after the cattle herds were moved elsewhere to a different location on the farm, outside the study area (20-Jun-2017–05-Oct-2017), and until the end of the experiment in December 2017.

2.3. Method of GHG sample collection and concentration measurement

The non-flow-through, non-steady-state GHG chamber technique was used (also known as closed static chamber) (Rochette, 2011) to collect headspace gas samples. Each sampling point along the savanna transects was composed of three PVC chambers, each consisting of a frame inserted 5 cm into the soil and a removable lid (length × width × height = 37 cm × 26.5 cm × 11.5 cm). For the sampling points in the bomas, the lids were placed directly in the manure, and height of the manure inside the chambers was measured to correct the volume of the chamber headspace. Each lid was fitted with a fan for headspace air mixing, a vent tube for pressure equilibration, and a thermometer port to measure headspace temperature during gas sampling. Gas samples were collected using the gas pooling technique (Arias-Navarro et al., 2013), where 20 ml of air were drawn from each replicate chamber using the same syringe to form a 60 ml composite air sample for each sampling

Fig. 1. Boma infrastructure at the study site. (photo credit: Lutz Merbold).

Table 1
Boma cattle numbers and manure accumulation for the different seasons and boma periods. „Active boma", cattle were enclosed in the boma at nighttime; „inactive boma", cattle had been moved elsewhere and there was no fresh manure input into that boma; Boma A-C are replicates; FW, fresh weight; DW, dry weight.

Season	Period	Start-End (days)	Replicate	Cattle number (head)	Fresh manure (Mg FW)	Dry manure (Mg DW)	Manure-C (Mg C)	Manure-N (kg N)	Manure volatile solids (Mg VS)*
Dry season	Boma I (active)	09.11.2016–01.02.2017 (85)	Boma A	139	153.6	28.8	9.9	422	23.4
			Boma B	95	105.0	19.7	6.8	288	16.0
			Boma C	156	172.4	32.3	11.1	473	26.3
	Boma II (active)	02.02.2017–15.03.2017 (42)	Boma A	164	89.5	16.8	5.8	246	13.7
			Boma B	159	86.8	16.3	5.6	238	13.3
			Boma C	118	64.4	12.1	4.2	177	9.8
Wet season	Boma III (active)	16.03.2017–28.04.2017 (44)	Boma A	164	93.8	17.6	6.0	258	14.3
			Boma B	156	89.2	16.7	5.8	245	13.6
			Boma C	123	70.3	13.2	4.5	193	10.7
	Boma IV (active)	29.04.2017–24.05.2017 (27)	Boma A	170	57.5	10.8	3.7	158	8.8
			Boma B	161	54.4	10.2	3.5	149	8.3
			Boma C	119	40.2	7.5	2.6	110	6.1
Dry season	Boma V (active)	25.05.2017–20.06.2017 (26)	Boma A	121	42.5	8.0	2.7	117	6.5
			Boma B	147	51.6	9.7	3.3	142	7.9
			Boma C	115	40.4	7.6	2.6	111	6.2
Dry & wet season	Boma V (inactive)	21.06.2017 -07.12.2017 (171)	Boma A	0	-	-	-	-	-
			Boma B	0	-	-	-	-	-
			Boma C	0	-	-	-	-	-

* Manure volatile solids (VS) were calculated assuming an ash content of 18.5% DM (Korir et al., 2022).

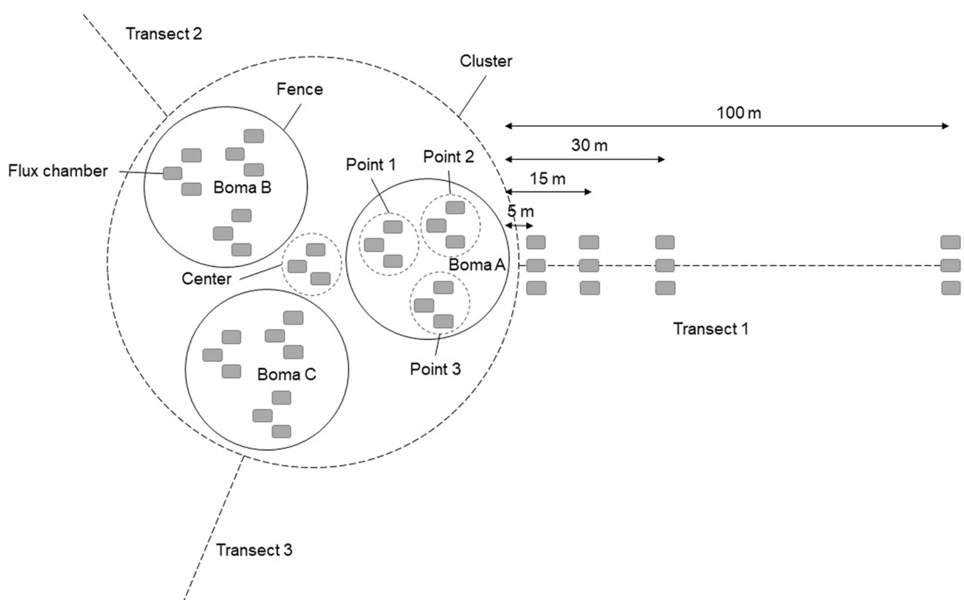

Fig. 2. Deployment of replicate bomas (Boma A, B, C) and flux chambers (grey boxes) for GHG sampling at the study site. Inside each boma, three sampling points composed of three replicate chambers for gas pooling were set up. In addition, three transects composed of five sampling points (each containing three chambers for gas pooling) were set at the center of the first boma cluster ("Center") and at four distances (5 m, 15 m, 30 m, and 100 m) from the initial boma positions (Boma position I) at the beginning of the experiment in November 2016. Transect positions remained the same throughout the experiment, while flux chambers inside bomas were relocated following the boma positions, which were moved by a few meters every 1–3 months (Boma periods I to V).

point. 35 ml of the sample were flushed through a 10 ml gas vial to remove ambient air, and the remaining 25 ml of gas were filled into the vial, resulting in a slight overpressure. After closing the chamber lids, four gas samples were taken at 0, 12, 24 and 36 minutes (in the bomas) and at 0, 15, 30 and 45 minutes (in the savanna) to ensure points to stay within linear concentration increase. From June 2017 until the end of the experiment, sampling time was reduced to 0, 6, 12 and 18 minutes in bomas and savanna transects to ensure that all points stay within the time of linear concentration increase. Gas samples were stored at room temperature and were transported to ILRI's Mazingira Centre for Environmental Research and Education (https://mazingira.ilri.org) in Nairobi within ≤2 weeks after sampling, where they were analysed for CH_4, N_2O and CO_2 concentrations using a gas chromatograph (GC; SRI Instruments, model 8610 C). The GC was fitted with a flame ionization detector (FID) equipped with a methanizer for CH_4 and CO_2, and a ^{63}Ni electron capture detector (ECD) for N_2O, both heated to 350 ºC. The GC column oven was run at 70 ºC, and the flow rate for the carrier gas (N_2) was 25 ml min^{-1} (Leitner et al., 2021). Calibration gases with known CH_4, N_2O and CO_2 concentrations (ranging from 4.28–49.80 ppm for CH_4, 360–2530 ppb for N_2O, and 400–2420 ppm for CO_2) were injected at the beginning and after every 20–30 samples to determine headspace gas sample concentrations. These were calculated through the relation of peak areas of samples and peak areas of calibration gases, using a linear regression for CH_4 and CO_2 (Eq. (1)) and a power regression for N_2O that leads to a better fit due to the non-linearly behaviour of the ECD (Eq. (2)):

$$Conc_{CH_4,CO_2} = \alpha x + \beta \quad (1)$$

$$Conc_{N_2O} = \alpha x^{\beta} \quad (2)$$

where $Conc_{CH_4,CO_2}$ are the methane and carbon dioxide concentrations (ppm), $Conc_{N_2O}$ is the concentration of nitrous oxide (ppb), x is the sample peak area from the GC, and α and β are model coefficients from the calibration curve.

2.4. GHG flux calculation

Greenhouse gas flux rates for bomas and savanna transects were calculated from the linear change in gas concentration in the chamber headspace over the chamber closure time, corrected for mean chamber temperature and air pressure (Metcalfe et al., 2007) (Eq. (3))

$$F_{GHG} = \frac{\delta_c}{\delta_t} * \frac{P}{1013} * \frac{273}{(T+273)} * \frac{M}{22.41} * \frac{V}{A} \quad (3)$$

where F_{GHG} is the greenhouse gas flux (mg CO_2-C m^{-2} h^{-1}, µg CH_4-C m^{-2} h^{-1}, and µg N_2O-N m^{-2} h^{-1}), $\delta c/\delta t$ is the change of gas concentration over time (i.e. slope, in ppmv h^{-1} for CO_2, and ppbv h^{-1} for N_2O and CH_4), P is the air pressure at the study site (mbar), 1013 is the air pressure at sea level (mbar), T is the mean chamber headspace temperature during deployment (℃), M is the molar mass of nitrogen (2 ×14 = 28 for N_2O) or carbon (12 for CH_4 and CO_2), 22.41 is the Ideal Gas Volume (L mol^{-1}), V is the chamber headspace volume (m^3), and A is the area covered by the chamber (m^2).

Calculated GHG fluxes were discarded if the correlation coefficient (r) of the linear slope of $\delta c/\delta t$ was <0.9 for CO_2 and <0.8 for CH_4 and N_2O. Moreover, we also discarded fluxes for N_2O and CH_4 with r<0.9 for CO_2 fluxes, assuming that the chamber was leaking.

Cumulative GHG emissions were calculated by trapezoidal integration. For this, data gaps were filled with a running mean (window size ±4 data points, linear weighting), then hourly fluxes were multiplied with *24 to derive daily fluxes and summed over the respective periods. To calculate manure-induced GHG emissions (i.e., emissions that were caused by deposition of manure onto the soil), cumulative GHG emissions from bomas were corrected for background soil GHG emissions by subtracting them with cumulative emissions from the transect at 30 m distance from bomas (since the point at 100 m distance was only added in the second half of the study).

Emission factors (EF) were calculated following Eqs. (4) and (5) below and expressed as % manure-C that was emitted as CO_2-C or CH_4-C, and % manure-N that was emitted as N_2O-N:

$$EF_{CH4} \& EF_{CO2}(\%) = \frac{Cumulative\,manure\,CH_4\,or\,CO_2\,emissions\,(kg\,C\,boma^{-1})}{C\,in\,accumulated\,manure\,(kg\,C\,boma^{-1})} * 100 \quad (4)$$

$$EF_{N2O}(\%) = \frac{Cumulative\ manure\ N_2O\ emissions\ (kg\ N\ boma^{-1})}{N\ in\ accumulated\ manure\ (kg\ N\ boma^{-1})} * 100 \quad (5)$$

To allow comparison with IPCC default values, CH_4 EFs were also calculated based on excreted volatile solids (VS) following Eq. (6) and expressed as g CH_4 kg^{-1} VS (IPCC, 2019):

$$EF_{CH4\_VS}(g\,CH_4\,kg^{-1}\,VS) = \frac{Cumulative\,manure\,induced\,CH_4\,(g\,CH_4\,boma^{-1})}{VS\,in\,accumulated\,manure\,(kg\,VS\,boma^{-1})} \quad (6)$$

To compare the contribution of different livestock emission sources at the farm scale, emissions of CH_4 and N_2O from boma manure were calculated using the manure EFs from this study converted to a per-animal basis using a manure excretion rate of 2.4 ± 0.3 kg DW per night (see Section 2.5). Furthermore, emissions of CH_4 and N_2O from manure deposited on pasture were estimated using EFs from Zhu et al. (2021a) for manure from Kenyan cattle, and enteric CH_4 emissions were estimated using emission factors from Wolz et al. (2022) for Boran cattle from the same farm as the present study. All manure emission factors were multiplied by the total number of cattle at the farm (3800). Grassland emissions were calculated by multiplying the total area of grassland without bomas on the farm (10,400 ha) by the emissions per area measured at 100 m distance from the bomas. The area around the bomas was not taken into account, so the emission estimates are conservative. All emissions were converted to CO_2-equivalent (CO_2eq) using a 100-year global warming potential (GWP) of 28 for CH_4 and 265 for N_2O (calculated on a per-mass basis and including climate-carbon feedback effects, IPCC, 2013, p. 714).

2.5. Soil and manure sampling

At the beginning of the experiment, soil samples from two profiles inside bomas and two profiles in the savanna soil were taken. From each profile, four replicate samples were collected at 0–5, 5–10, 10–20, 20–40, 40–70 and 70–100 cm depth. At each depth, samples for bulk density and water content were collected with stainless-steel cylinders of 5.6 cm diameter and 4 cm height (100 cm^3 volume) at each soil depth, individually packed in zip-lock bags and transported to the lab within 5 days. A forced-air oven was used to dry the soil samples to constant weight at 105°C for 48 hours.

After the end of the experiment, soil samples were taken at each GHG sampling point to determine C and N concentration, pH, water content and bulk density. Four replicates were taken at 0–5, 5–20 and 20–50 cm depths. Three replicates were pooled into one sample for C, N, and pH analysis. The pooled samples were oven-dried at 60°C overnight and analysed for C and N with an elemental combustion system (VarioMAX Cube elemental analyser, Elementar GmbH, Hanau, Germany) and for pH with a pH meter in water solution (1:2.5). The fourth replicate was oven dried to constant weight at 105°C for 48 hours to determine bulk density and water content.

To estimate the amount of manure that accumulated in each period in the bomas, three to four cattle were enclosed in a separate small boma overnight that was lined with a waterproof tarp on the floor, and total dung and urine were collected each morning, weighed, and subsampled for analysis of water, C and N content. This was done on 23 separate occasions between June and September 2019. Manure volatile solids (VS) were calculated following Eq. (7) by subtracting manure ash content from manure dry matter (DM) (IPCC, 2019):

$$VS(g) = DM(g) - ASH(g) \quad (7)$$

assuming an ash content of 18.5% DM (as measured for *Boran* cattle fed on tropical forage grass in Kenya, Korir et al., 2022).

2.6. Environmental data

A weather station at the sampling site fitted with a data logger (EM50, Decagon, Pullman, WA; USA) recorded environmental data throughout the experiment every 15 min. Air temperature and relative humidity were measured with a temperature/relative humidity sensor (ATMOS 14, Decagon, Pullman, WA; USA). Precipitation was recorded with a tipping rain gauge (ECRN-100 high-resolution, Decagon, Pullman, WA; USA). Soil water content and temperature in the bomas and in the savanna soils were measured with Decagon 5TM soil sensors at 5 cm depth. Wind speed and direction were recorded every 15 min (mean of 1-minute intervals) with an anemometer (Davis cup Anemometer, Decagon, Pullman, WA; USA).

2.7. Data analysis

Gap filling for cumulative emission calculation was done using the package "imputeTS" (Moritz and Bartz-Beielstein, 2017). Differences in GHG flux rates and cumulative GHG emissions between season (dry versus wet), location (boma, center, 5 m, 15 m, 30 m, 100 m), status (active versus inactive boma), and their interactions were tested with an ANOVA using the *aov* function of the "stats" package (base R) on cube-root transformed data (cube-root transformation can be applied on positive and negative values). Because GHG fluxes and cumulative emissions from bomas were orders of magnitude larger than those from transect points, residuals were not normally distributed, and data were heteroscedastic (i.e., variance was not homogeneous) despite data transformation. Consequently, the dataset was split into boma data and transect data, and a two-way ANOVA was run on the boma dataset with

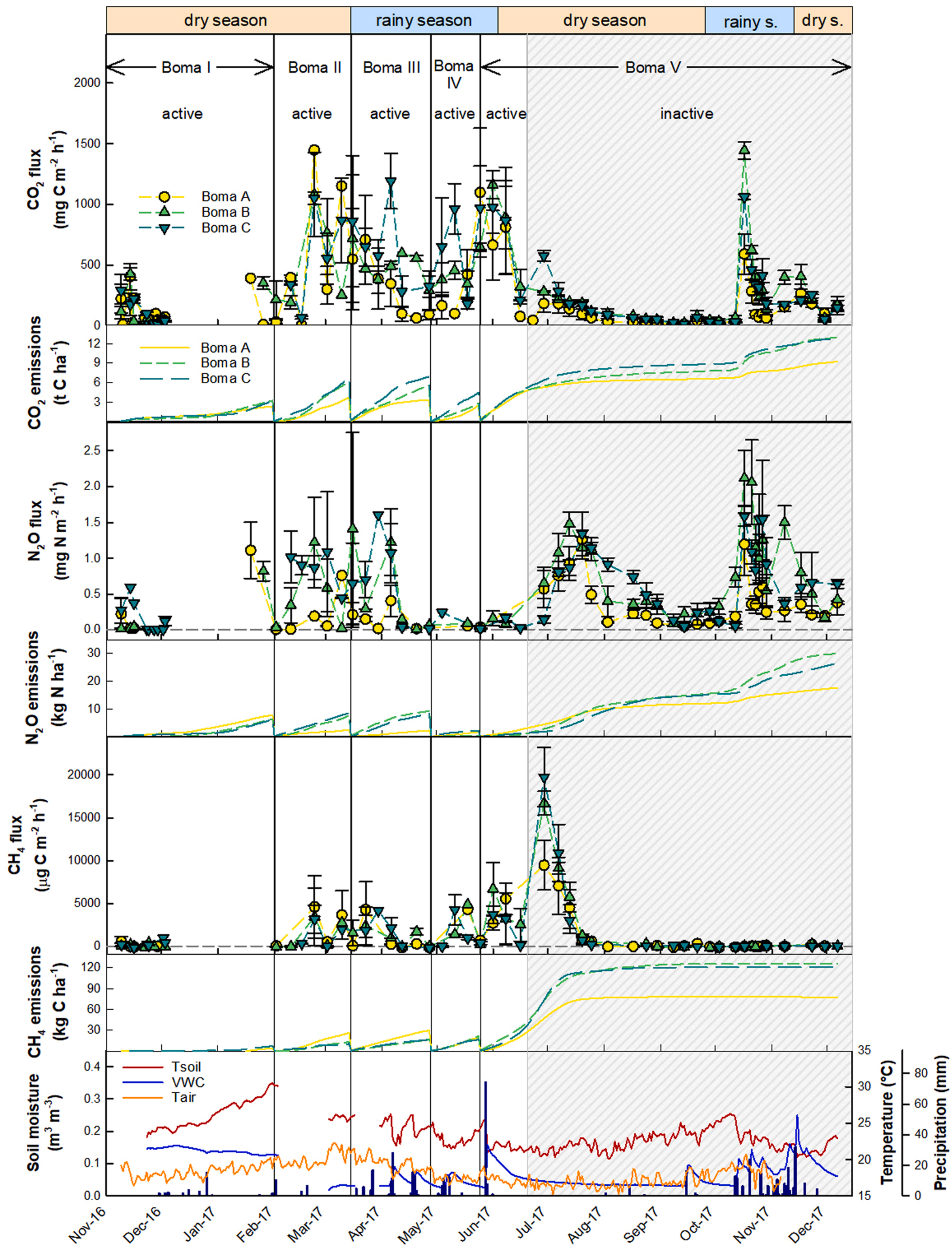

Fig. 3. Fluxes of CO_2 (mg C m^{-2} h^{-1}), N_2O (µg C m^{-2} h^{-1}) and CH_4 (µg C m^{-2} h^{-1}) as well as cumulative emissions of CO_2 (t C ha^{-1}), CH_4 (kg C ha^{-1}) and N_2O (kg N ha^{-1}) from bomas from Nov-2016 to Dec-2017. The bottom panel shows daily means of air temperature (Tair, °C), soil temperature (Ts, °C), volumetric moisture content (VWC, m^3 m^{-3}) measured in the bomas (5 cm depth), and daily rainfall sums (mm). Vertical lines labelled "Boma I" to "Boma V" represent dates when boma clusters were moved to a new spot. Bomas A-C are replicate bomas, each of which contained 9 replicate soil flux chambers.

season (dry versus wet), status (active versus inactive), and their interactions as fixed factors. For the transects, an ANCOVA was run with distance from the boma in m as numeric variable (2 m for Center, 5 m, 15 m, 30 m, and 100 m), and season (dry versus wet) as categorical variables. All statistical analyses were done with RStudio 2022.07.2 using R version 4.2.1 (R Core Team, 2019). ANOVA and ANCOVA were calculated using the *aov* function of the "stats" package in base R, and group differences were compared with Tukey's HSD test using the *emmeans* function from the "emmeans" package (Lenth, 2023). Correlations between GHG fluxes, environmental parameters, and soil properties were analysed with a Spearman correlation test using the *cor.test* function ("stats" package). Annual EFs for N_2O and CH_4 were compared to the IPCC default factors for drylots with a t-test using the *t.test* function ("stats" package). Results of statistical significance testing are given in Tables S2, S3, and S4. We only report significant differences in the text unless explicitly stated otherwise. Data are expressed as mean ± standard deviation.

3. Results

3.1. Soil characteristics and environmental factors

Annual precipitation at the study location was 506 mm between 07-Dec-2016 and 07-Dec-2017, with 84% of the precipitation falling during the two rainy seasons (mid-March to end of May and October to mid-November). Mean annual air temperature was 18.1°C and mean monthly air temperature ranged from 16.8°C in July to 20.3°C in March (Fig. 3).

Soil characteristics at the locations of bomas and savanna transects at the start of the experiment are given in Table S1. There were no significant differences between transect and boma soil. The soil was neutral with a pH of 7.1 ± 0.2. Soil C decreased with soil depth and was 1.55 ± 0.09% (0–5 cm), 0.83 ± 0.03% (5–20 cm), and 0.54 ± 0.04% (20–50 cm). Similarly, soil N decreased with soil depth and was 0.13 ± 0.01% (5–20 cm), 0.06 ± 0.003% (5–20 cm), and 0.05 ± 0.004% (20–50 cm). Soil C/N ratio was 12.8 ± 0.5 and did not change with soil depth because soil C and N concentrations were highly correlated over all depth layers ($r=0.986$, $p<0.001$). Bulk density was 1.37 ± 0.04 g m^{-3} in the topsoil (0–5 and 5–20 cm) and decreased to 1.12 ± 0.20 g m^{-3} in the subsoil (20–50 cm).

Manure in the bomas accumulated up to a 30 cm layer for the longest study period (Boma period I, 85 days). The amount of manure deposited per cattle overnight was 13.0 ± 1.5 kg FW, corresponding to 2.4 ± 0.3 kg DW. Manure C and N concentrations in fresh manure did not differ between dry and wet seasons and were 34.4 ± 1.04%C and 1.47 ± 0.11%N, with a C/N ratio of 23.6 ± 2.4. Because manure accumulation is a function of animal numbers and duration of active boma use, the amount of manure that accumulated in the different bomas varied over time: the largest accumulation was observed in Boma Period I (85 days), with a manure accumulation of 144 ± 20 Mg FW or 26.9 ± 3.8 Mg DW, corresponding to 9.3 ± 1.3 Mg C, 394 ± 55 kg N, and 21.9 ± 3.1 Mg VS per boma (Table 1). In contrast, during Boma period IV, which was the shortest active time (26 days), bomas accumulated 3-times less manure, namely 50.7 ± 5.3 Mg FW or 9.5 ± 1.0 Mg DW, corresponding to 3.3 ± 0.3 Mg C, 139 ± 15 kg N, and 7.7 ± 0.8 Mg VS per boma.

3.2. Carbon dioxide flux rates and cumulative emissions

CO_2 flux rates ranged from 8-1937 mg C m^{-2} h^{-1} in active bomas and from 6-1580 mg C m^{-2} h^{-1} in inactive bomas and peaked during the rainy season and after rainfall events in the dry season (Fig. 3). Mean CO_2 fluxes in active bomas did not differ between dry season (409 ± 181 mg C m^{-2} h^{-1}) and wet season (497 ± 112 mg C m^{-2} h^{-1}) (Table 2, Fig. 5). In contrast, mean CO_2 fluxes from inactive bomas were 3-times higher in the rainy season (305 ± 62 mg C m^{-2} h^{-1}) than in the dry season (98 ± 15 mg C m^{-2} h^{-1}). Mean CO_2 fluxes from adjacent savanna were a factor 2–15 lower than from bomas and decreased with increasing distance from bomas (ranging from 121 ± 85 mg C m^{-2} h^{-1}

Table 2
Flux rates of N_2O (μg N m^{-2} h^{-1}), CH_4 (mg C m^{-2} h^{-1}) and CO_2 (mg C m^{-2} h^{-1}) and cumulative emissions (kg N_2O-N ha^{-1}, kg CH_4-C ha^{-1}, Mg CO_2-C ha^{-1}) from bomas and transects for the wet seasons (mid-Mar to end of May and mid-Oct to end of Nov, 123 days), dry seasons (242 days), and over a full year. Points along the transect were taken in the center of the boma cluster ('Center'), and with increasing distance (5, 10, 30 and 100 m) from the initial boma location (see Fig. 2 for the study layout). Values are means ± SD (n = 3). Significant differences between dry and wet season are marked with lowercase letters (a, b), differences between active and inactive bomas are marked with capital letters (A, B).

Location	Season	CO_2 flux mg C m^{-2} h^{-1}	N_2O flux μg N m^{-2} h^{-1}	CH_4 flux μg C m^{-2} h^{-1}	Cum. CO_2 emissions* Mg C ha^{-1}	Cum. N_2O emissions* kg N ha^{-1}	Cum. CH_4 emissions* kg C ha^{-1}
Bomas							
Active	Dry season	490 ± 313^{B}	292 ± 277	3639 ± 3052	3.54 ± 2.10^{B}	2.96 ± 1.71	17.28 ± 17.56
	Wet season	497 ± 195	382 ± 372 ^{A}	3150 ± 1836^{B}	3.60 ± 1.07	3.05 ± 2.38	17.81 ± 5.33^{B}
	Annual	487 ± 8^{B}	325 ± 11^{A}	3245 ± 234	43.30 ± 8.72^{B}	36.37 ± 7.38	212.39 ± 14.56
Inactive	Dry season	98 ± 27^{A}	498 ± 108	4718 ± 1862^{b}	0.87 ± 0.27^{A}	3.57 ± 0.91	18.96 ± 4.94^{b}
	Wet season	305 ± 108	829 ± 345^{B}	-5 ± 84^{Aa}	1.84 ± 0.56	5.06 ± 2.19	-0.03 ± 0.67^{Aa}
	Annual	167 ± 52^{A}	610 ± 186^{B}	3127 ± 1262	14.58 ± 4.14^{A}	49.55 ± 16.26	152.77 ± 42.48
Transect							
Center	Dry season	82.6 ± 62.8^{a}	15.8 ± 14.2^{a}	96.3 ± 346.5	0.57 ± 0.17^{a}	0.11 ± 0.06^{a}	0.50 ± 1.04
	Wet season	191.7 ± 78.6^{b}	45.8 ± 31.8^{b}	235.9 ± 225.6	1.40 ± 0.36^{b}	0.35 ± 0.20^{b}	1.17 ± 1.56
	Annual	121.1 ± 85.3	28.6 ± 27.3	145.6 ± 309.3	10.31 ± 2.79	2.30 ± 1.26	8.85 ± 14.67
5 m	Dry season	65.8 ± 81.7^{a}	18.6 ± 24.2^{a}	42.2 ± 53.6	0.42 ± 0.36^{a}	0.13 ± 0.12^{a}	0.36 ± 0.21
	Wet season	161.5 ± 120.0^{b}	62.2 ± 72.5^{b}	67.1 ± 95.1	1.19 ± 0.90^{b}	0.45 ± 0.37^{b}	0.46 ± 0.37
	Annual	111.1 ± 110.2	37.3 ± 54.0	54.0 ± 74.9	8.24 ± 6.59	2.87 ± 2.50	4.75 ± 3.05
15 m	Dry season	55.7 ± 35.0^{a}	16.5 ± 16.5^{a}	6.7 ± 83.8	0.35 ± 0.07^{a}	0.11 ± 0.05^{a}	0.04 ± 0.39
	Wet season	104.1 ± 69.8^{b}	35.8 ± 20.9^{b}	5.2 ± 47.2	0.78 ± 0.09^{b}	0.25 ± 0.08^{b}	0.05 ± 0.31
	Annual	79.9 ± 59.1	24.8 ± 20.5	6.0 ± 66	6.04 ± 0.94	1.92 ± 0.70	0.54 ± 4.40
30 m	Dry season	35.5 ± 29.1^{a}	11.0 ± 12.6^{a}	8.8 ± 46.3	0.27 ± 0.19^{a}	0.08 ± 0.08^{a}	0.10 ± 0.27
	Wet season	126.3 ± 101.0^{b}	17.7 ± 16.9^{b}	-8.4 ± 44.9	0.93 ± 0.60^{b}	0.13 ± 0.13^{b}	0.00 ± 0.20
	Annual	72.9 ± 80.2	13.9 ± 14.6	1.7 ± 45.1	5.96 ± 3.94	1.17 ± 1.16	0.80 ± 2.95
100 m	Dry season	6.9 ± 0.1^{a}	1.4 ± 1.0	-1.4 ± 5.5	0.05 ± 0.00^{a}	0.01 ± 0.01	-0.01 ± 0.03
	Wet season	52.8 ± 16.8^{b}	4.2 ± 3.1	1.4 ± 4.5	0.38 ± 0.11^{b}	0.03 ± 0.03	0.01 ± 0.03
	Annual	22.3 ± 18.2	2.5 ± 2.2	0.1 ± 0.7	1.95 ± 0.49	0.22 ± 0.17	0.01 ± 0.33

* To account for different lengths of boma periods and seasons, cumulative emissions for dry and wet season were calculated for 30 days (kg or Mg C ha^{-1} $month^{-1}$ or kg N ha^{-1} $month^{-1}$), and annual emissions were calculated for 365 days using 123 wet-season days and 242 dry-season days (kg or Mg C ha^{-1} $year^{-1}$ or kg N ha^{-1} $year^{-1}$).

in the Centre to 22 ± 18 mg C m^{-2} h^{-1} at100 m distance) (Fig. 4, Fig. 5). Furthermore, there was a strong effect of seasonality on savanna CO_2 fluxes, with 2–5 times higher fluxes observed in the rainy season than in the dry season (Table 2). CO_2 fluxes were positively correlated with soil moisture ($p<0.001$, r=0.55).

Calculated over a full year, cumulative CO_2 emissions from active bomas (43.3 ± 21.3 Mg C ha^{-1} $year^{-1}$) were 4–20 times higher than from adjacent savanna soils (ranging from 10.3 ± 2.8 Mg C ha^{-1} $year^{-1}$ in the Centre to 2.0 ± 0.5 Mg C ha^{-1} $year^{-1}$ at 100 m) (Table 2). After bomas were abandoned, annual cumulative CO_2 emissions were similar between bomas (14.6 ± 4.5 Mg C ha^{-1} $year^{-1}$) and nearby savanna soils (Center and 5 m) and decreased with increasing distance (>15 m). When corrected for background savanna respiration, cumulative manure-induced CO_2 emissions in active bomas did not vary between dry season (3.39 ± 1.14 Mg C ha^{-1} $month^{-1}$) and wet season (2.89 ± 1.16 Mg C ha^{-1} $month^{-1}$) (Table 3). Similarly, in inactive bomas cumulative manure-induced CO_2 emissions were similar between dry season (0.57 ± 0.25 Mg C ha^{-1} $month^{-1}$) and wet season (0.16 ± 0.82 Mg C ha^{-1} $month^{-1}$), but they were ca. 5–10 times lower than in active bomas. Calculated for a full year (assuming 123 wet-season days per year), cumulative manure-induced CO_2 emissions from active bomas (39.2 ± 13.9 Mg C ha^{-1} $year^{-1}$ or 2.7 ± 0.88 Mg C $boma^{-1}$ $year^{-1}$) were eight times higher than from inactive bomas (5.24 ± 5.37 Mg C ha^{-1} $year^{-1}$ or 0.42 ± 0.24 Mg C $boma^{-1}$ $year^{-1}$). The EF_{CO2} for active bomas were similar in the dry season (6.85 ± 2.57%C) and wet season (6.19 ± 1.82%C), but they were higher for active than for inactive bomas (1.39 ± 0.41%C for the dry season and 0.77 ± 0.37%C for the wet season). Calculated over a full year and assuming 45 days of active boma use, the annual boma EF_{CO2} was 12.6 ± 5.3%C.

3.3. Nitrous oxide flux rates and cumulative emissions

N_2O flux rates from active bomas ranged from 1 to 1222 µg N m^{-2} h^{-1} (mean 292 ± 277 µg N m^{-2} h^{-1}) in the dry season, and from 3 to 1607 µg N m^{-2} h^{-1} (mean 382 ± 372 µg N m^{-2} h^{-1}) in the wet season (Fig. 3, Table 2), with no significant differences between seasons (Fig. 5). In inactive bomas, N_2O flux rates were higher in the wet season (823 ± 345 µg N m^{-2} h^{-1}) than in the dry season (498 ± 108 µg N m^{-2} h^{-1}) (Fig. 3, Table 2). In the adjacent savanna soils, N_2O flux rates were up to a factor of 20 lower than from bomas, and N_2O fluxes further decreased with increasing distance from the bomas (Fig. 4, Table 2), but these differences were not significant due to the large data variability (Fig. 5). N_2O flux rates from savanna soils increased after rainfall events, and mean N_2O fluxes were higher in the rainy season in the vicinity of the bomas (≤30 m). N_2O fluxes were positively correlated with soil moisture (r=0.21, $p<0.001$).

Cumulative N_2O emissions from active bomas were 10–100 times higher than from adjacent savanna soils in both dry and wet season (Table 2). There was no difference in cumulative N_2O emissions from active bomas between seasons, or when comparing active and inactive bomas. Cumulative N_2O emissions from adjacent savanna soils decreased with increasing distance from bomas and were higher in the wet season than in the dry season. Calculated over a full year, cumulative N_2O emissions from active bomas (36.37 ± 7.38 kg N ha^{-1} $year^{-1}$) and inactive bomas (49.55 ± 16.26 kg N ha^{-1} $year^{-1}$) were 12–40 times higher than from adjacent savanna soils (≤30 m), and up to 200-times higher than from the most distant savanna point at 100 m (0.22 ± 0.17 kg N ha^{-1} $year^{-1}$) (Table 2).

Manure-induced N_2O emissions (Table 4) in active bomas were similar between dry season (2.74 ± 0.80 kg N ha^{-1} $month^{-1}$) and wet season (3.15 ± 0.76 kg N ha^{-1} $month^{-1}$). Similarly, manure-induced N_2O emissions from inactive bomas were in the same range and did not differ between dry season (3.50 ± 0.55 kg N ha^{-1} $month^{-1}$) and wet season (4.88 ± 1.37 kg N ha^{-1} $month^{-1}$). Consequently, EF_{N2O} for active bomas were similar for both seasons (0.14 ± 0.05%N), as were EF_{N2O} for inactive bomas in both the dry season (0.20 ± 0.03%N) and wet season (0.28 ± 0.07%N) (Table 3). Annual manure-induced N_2O emissions were similar between active (35.0 ± 8.94 kg N ha^{-1} $year^{-1}$) and inactive bomas (48.3 ± 10.0 kg N ha^{-1} $year^{-1}$). N_2O emissions calculated over a full year assuming 45 days of active boma use resulted in an annual EF_{N2O} of 2.43 ± 0.42%N, which is similar to the IPCC default EF_{N2O} for feedlots for low-producing non-dairy cattle (2.0 ± 1.0%N) (t=1.77, p=0.109) (IPCC, 2019).

3.4. Methane flux rates and cumulative emissions

Methane flux rates ranged from −194–6690 µg C m^{-2} h^{-1} (mean 3443 ± 2567 µg C m^{-2} h^{-1}) in active bomas and from −167–19750 µg C m^{-2} h^{-1} (mean 2357 ± 2834 µg C m^{-2} h^{-1}) in inactive bomas (Fig. 3, Table 2). Short-lived CH_4 pulses in active and inactive bomas were observed after rain events, and the highest single CH_4 flux (25,200 µg C m^{-2} h^{-1}) was measured four weeks after a large rain event (ca. 100 mm precipitation in three days) in a boma that had recently been abandoned. There was no difference in mean CH_4 fluxes from active bomas between dry season and wet season (Fig. 5,Table 2), but we found that in inactive bomas, mean CH_4 flux rates were higher in the dry season (4718 ± 1862 µg C m^{-2} h^{-1}) than in the wet season (-5 ± 84 µg C m^{-2} h^{-1}) because of the large rain-induced CH_4 pulses mentioned above.

Compared to active bomas, CH_4 fluxes from adjacent savanna soils were 10–50 times lower or slightly negative (Fig. 4). Savanna soil CH_4 flux was highest after rain events and when cattle were present in the study area. Mean CH_4 fluxes from savanna soils were highest in the vicinity of the bomas and decreased with increasing distance (ranging from 145 ± 309 µg C m^{-2} h^{-1} in the Centre to 0.1 ± 0.7 µg C m^{-2} h^{-1} at 100 m) (Table 2). When calculated over the entire study duration, CH_4 fluxes did not differ between savanna transect locations. However, when calculated only for the times that cattle were present in the study area and there was fresh manure input (09-Nov-2016 until 19-Jun-2017 and 06-Oct-2017 until 07-Dec-2017), CH_4 fluxes increased significantly with increasing vicinity to bomas (Table S2). CH_4 fluxes were not correlated with soil moisture or temperature.

Cumulative CH_4 emissions from active bomas were not different between dry season and wet season (Table 2). In contrast, cumulative CH_4 emissions from inactive bomas were higher in the dry season than in the wet season. Similar to CH_4 flux rates, annual cumulative CH_4 emissions from active bomas (212 ± 164 kg C ha^{-1} $year^{-1}$) and inactive bomas (153 ± 43 kg C ha^{-1} $year^{-1}$) were 20–100 times larger than from adjacent savanna soils, where emissions decreased with increasing distance from bomas (ranging from 8.9 ± 14.7 kg C ha^{-1} $year^{-1}$ in the Centre to 0.01 ± 0.33 kg C ha^{-1} $year^{-1}$ at 100 m).

Cumulative manure-induced CH_4 emissions from active bomas were similar between dry season (17.6 ± 7.2 kg C ha^{-1} $month^{-1}$) and wet season (17.3 ± 4.3 kg C ha^{-1} $month^{-1}$) (Table 5). In inactive bomas, manure-induced CH_4 emissions were higher in the dry season (18.7 ± 3.1 kg C ha^{-1} $month^{-1}$) than in the wet season (-0.2 ± 0.7 kg C ha^{-1} $month^{-1}$). Consequently, for EF_{CH4}, there was no difference between dry season (0.04 ± 0.02%C) and wet season (0.03 ± 0.01%C) for active bomas (Table 5), whereas for inactive bomas the EF_{CH4} was 0.05 ± 0.01%C in the dry season and zero in the wet season. Calculated over a full year and assuming 45 days of active boma use, bomas had an annual EF_{CH4} of 0.49 ± 0.07%C. Calculated following the IPCC method based on manure VS excretion, the annual EF_{CH4_VS} in this study was 2.64 ± 0.37 g CH_4 kg^{-1} VS, which was not different from the IPCC default value for feedlots for low-producing non-dairy cattle in warm climates, which is 1.70 ± 0.51 g CH_4 kg^{-1} VS (t=2.56, p=0.062).

3.5. GHG emissions at the farm scale

The Kapiti farm covers 10,400 ha of grassland and was holding a total of 3800 cattle during the study period. Calculated for the entire farm (Table 6), the total GWP of all livestock CH_4 sources was 8223 Mg

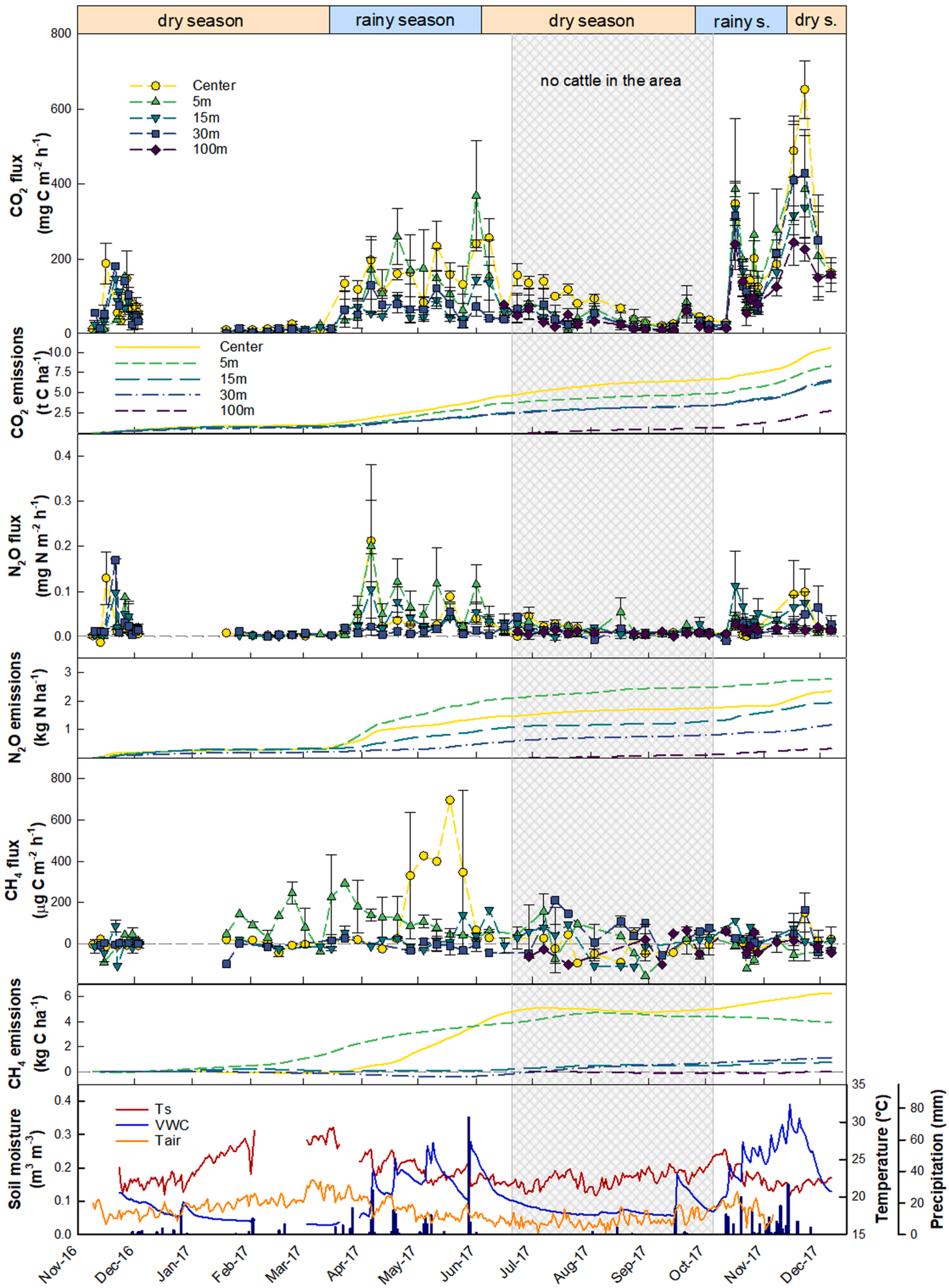

Fig. 4. Fluxes of CO_2 (mg C m^{-2} h^{-1}), N_2O (µg C m^{-2} h^{-1}) and CH_4 (µg C m^{-2} h^{-1}) as well as cumulative emissions of CO_2 (t C ha^{-1}), CH_4 (kg C ha^{-1}) and N_2O (kg N ha^{-1}) from savanna soils along a transect of increasing distance to cattle bomas (Center, 5, 15, 30, and 100 m) from Nov-2016 to Dec-2017. "Center" represents the location in the middle of the boma cluster. The bottom panel shows daily means of air temperature (Tair, °C), soil temperature (Ts, °C), volumetric moisture content (VWC, m^3 m^{-3}) measured in the bomas (5 cm depth), and daily rainfall sums (mm). The grey area represents the time when cattle were absent from the study area.

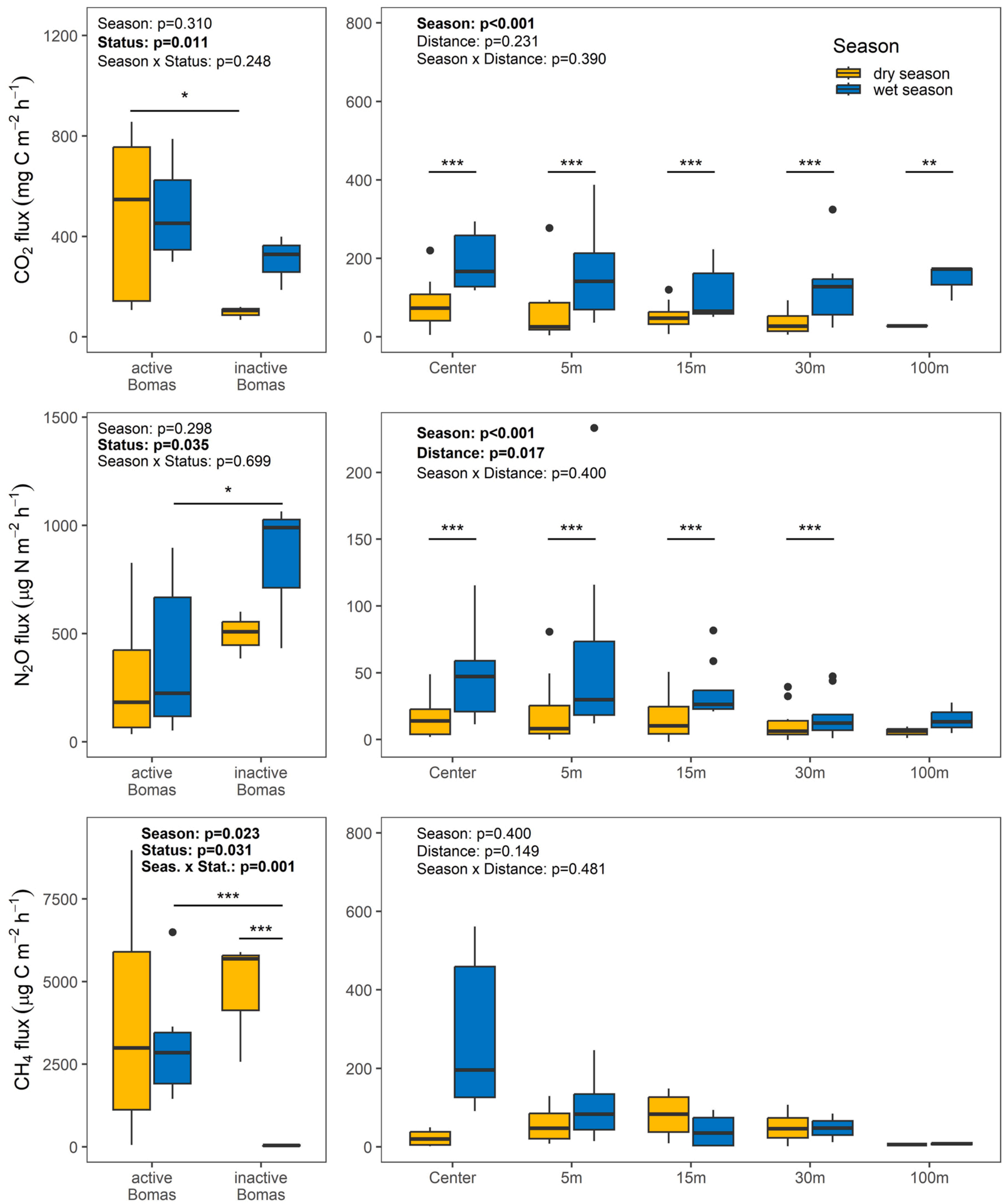

Fig. 5. Box and whisker plots of flux rates of CO_2, N_2O and CH_4 for bomas and transect locations with increasing distance from the bomas (Center, sampling point in the center of a cluster of 3 replicate bomas). Please note the difference in y-axis size of bomas versus transects. Significant results shown are from a two-way ANCOVA with season (dry versus wet) as categorical and distance from bomas (in m) as numerical variable. Asterisks denote significant differences between seasons at individual transect locations. See Tables S2 and S3 for full statistics results.

CO_2eq, to which enteric fermentation contributed 97.6% (8023 Mg CO_2eq). Manure was only a minor CH_4 source at the farm scale, with bomas contributing 2.2% (183 Mg CO_2eq) and manure deposited on pasture contributing 0.2% (13 Mg CO_2eq). CH_4 emissions from the grassland were negligible. In contrast, manure was an important source for farm-scale N_2O emissions, with bomas contributing 32.6% (990 Mg CO_2eq) and manure on pasture contributing 4.6% (140 Mg CO_2eq). CO_2 emissions are not included here because CO_2 from animals and manure originates from photosynthetic carbon (i.e., plant biomass) that is released via respiration and is therefore not considered to be a net contributor to anthropogenic CO_2 emissions (IPCC, 2006; Owen and Silver, 2015).

4. Discussion

4.1. Nitrous oxide emissions

In line with hypothesis 1, cattle bomas were significant sources of N_2O emissions at the landscape scale, contributing over 32% to farm-scale N_2O emissions. This is in line with a study from a savanna

Table 3
Manure-induced cumulative CO_2 emissions and CO_2 emission factors (EF_{CO2}, % manure-C emitted as CO_2-C) for active and inactive bomas, calculated for dry and wet season (Mg C ha^{-1} $month^{-1}$ and Mg C $boma^{-1}$ $month^{-1}$), and annually (Mg C ha^{-1} $year^{-1}$ and Mg C $boma^{-1}$ $year^{-1}$). Annual emissions are weighted for dry season days (242) and wet season days (123) per year. Total annual EF_{CO2} was calculated assuming 45 days of active boma use in one year. Significant differences between active and inactive bomas are marked with capital letters (A, B). Dry and wet season did not differ significantly.

Location	Season	Manure-induced cumulative CO_2 emissions	EF_{CO2}	
		(Mg C ha^{-1})	(Mg C $boma^{-1}$)	(% manure C emitted as CO_2-C)
Active bomas	Dry season	3.39 ± 1.14^B	0.23 ± 0.08	6.85 ± 2.57
	Wet season	2.89 ± 1.16^B	0.21 ± 0.07^B	6.19 ± 1.82^B
	Annual*	39.18 ± 13.88	2.71 ± 0.88	6.63 ± 2.32
Inactive bomas	Dry season	0.57 ± 0.25^A	0.04 ± 0.01	1.39 ± 0.41
	Wet season	0.16 ± 0.82^A	0.02 ± 0.03^A	0.77 ± 0.37^A
	Annual*	5.24 ± 5.37	0.42 ± 0.24	13.48 ± 5.72
Total bomas**	Annual	9.43 ± 6.26	0.71 ± 0.30	12.63 ± 5.30

*assuming 123 wet season days per year
**assuming 45 active use days per year

Table 4
Manure-induced cumulative N_2O emissions and N_2O emission factors (EF_{N2O}, % manure-N emitted as N_2O-N) for active and inactive bomas, calculated for dry and wet season (kg N ha^{-1} $month^{-1}$ and kg N $boma^{-1}$ $month^{-1}$) and annually (kg N ha^{-1} $year^{-1}$ and kg N $boma^{-1}$ $year^{-1}$). Annual emissions are weighted for dry season days (242) and wet season days (123) per year. Total annual EF_{N2O} was calculated assuming 45 days of active boma use in one year. Significant differences between active and inactive bomas are marked with capital letters (A, B). Dry and wet season did not differ significantly.

Location	Season	Manure-induced cumulative N_2O emissions	EF_{N2O}	
		(kg N ha^{-1})	(kg N $boma^{-1}$)	(% manure N emitted as N_2O-N)
Active bomas	Dry season	2.74 ± 0.80	0.19 ± 0.06	0.14 ± 0.04^A
	Wet season	3.15 ± 0.76	0.22 ± 0.05	0.14 ± 0.05^A
	Annual*	35.0 ± 8.94	2.47 ± 0.63	0.14 ± 0.05
Inactive bomas	Dry season	3.50 ± 0.55	0.25 ± 0.04	0.20 ± 0.03^B
	Wet season	4.88 ± 1.37	0.34 ± 0.10	0.28 ± 0.07^B
	Annual*	48.27 ± 10.02	3.41 ± 0.71	2.75 ± 0.47
Total bomas**	Annual	46.63 ± 9.84	3.30 ± 0.70	2.43 ± 0.42

* assuming 123 wet season days per year
**assuming 45 active use days per year

Table 5
Manure-induced cumulative CH_4 emissions and CH_4 emission factors (EF_{CH4}, % manure-C emitted as CH_4-N) for active and inactive bomas, calculated for dry and wet season (kg C ha^{-1} $month^{-1}$ and kg C $boma^{-1}$ $month^{-1}$) and annually (kg C ha^{-1} $year^{-1}$ and kg C $boma^{-1}$ $year^{-1}$). Annual emissions are weighted for dry season days (242) and wet season days (123) per year. Total annual EF_{CH4} was calculated assuming 45 days of active boma use in one year. Significant differences between dry and wet season are marked with lowercase letters (a, b), differences between active and inactive bomas with capital letters (A, B).

Location	Season	Manure-induced cumulative CH_4 emissions		EF_{CH4}
		(kg C ha^{-1})	(kg C $boma^{-1}$)	(% manure C emitted as CH_4-C)
Active bomas	Dry season	17.6 ± 7.2	1.2 ± 0.5	0.04 ± 0.02^A
	Wet season	17.3 ± 4.3^B	1.2 ± 0.3^B	0.03 ± 0.01^B
	Annual*	213.2 ± 75.6	14.9 ± 5.3	0.03 ± 0.02
Inactive bomas	Dry season	18.7 ± 3.1^b	1.3 ± 0.2^b	0.05 ± 0.01^{bB}
	Wet season	-0.2 ± 0.7^{aA}	0.0 ± 0.0^{aA}	0.00 ± 0.00^{aA}
	Annual*	150.0 ± 27.3	10.7 ± 2.1	0.55 ± 0.08
Total bomas**	Annual	157.8 ± 30.5	11.2 ± 2.3	0.49 ± 0.07

* assuming 123 wet season days per year
**assuming 45 active use days per year

steppe in Inner Mongolia reporting that cattle sheds contributed 34% to regional N_2O emissions (Chen et al., 2011). For cumulative manure N_2O emissions from livestock enclosures, the same study reported 17 kg N

Table 6
Farm-scale emissions from grassland, cattle bomas, enteric fermentation, and cattle manure deposited on pasture, expressed as CO_2-equivalents (CO_2eq).

Farm-scale emissions					
CH_4	Area (ha)	CH_4 emissions (kg CH_4 ha^{-1})	Farm-level CH_4 emissions (Mg CO_2eq)*		Source of emission factor
Grassland	10400	0.013	4	0.0%	This study
	Cattle (head)	EF_{CH4} (kg CH_4 $head^{-1}$)			
Cattle bomas	3800	1.72**	183	2.2%	This study
Enteric fermentation	3800	75.4	8023	97.6%	Wolz et al., (2022)
Manure on pasture	3800	0.12**	13	0.2%	Zhu et al., 2021
Total CH_4			8223	100%	
N_2O	Area (ha)	N_2O emissions (kg N_2O ha^{-1})	Farm-level N_2O emissions (Mg CO_2eq)*		Source of emission factor
Grassland	10400	0.691	1906	62.8%	This study
	Cattle (head)	EF_{N2O} (kg N_2O $head^{-1}$)			
Cattle bomas	3800	0.98**	990	32.6%	This study
Enteric fermentation	3800	-	-	-	
Manure on pasture	3800	0.14**	140	4.6%	Zhu et al., 2021
Total N_2O			3036	100%	

* CO_2eq were calculated using a GWP_{100} of 28 for CH_4 and 265 for N_2O ** Manure EF per head were calculated assuming a daily manure excretion rate of 2.4 kg DW $head^{-1}$ and manure chemical composition of 34.4%C and 1.47%N.

ha^{-1} $year^{-1}$ from summer cattle sheds, which was ca. 50% lower than found in the present study in Kenya for active bomas (36 kg N ha^{-1} $year^{-1}$) and inactive bomas (50 kg N ha^{-1} $year^{-1}$). This can be explained by the cold winters in Inner Mongolia, during which temperatures drop below zero, limiting microbial activity and N_2O formation (Butterbach-Bahl et al., 2013). In contrast, at our study site the minimum soil temperature never dropped below 9.5 °C and cattle bomas emitted considerable amounts of N_2O year-round. When calculated on a per-animal basis, this study found that cattle bomas emitted 0.98 kg N_2O $head^{-1}$ $year^{-1}$, which is within the range reported in a review of N_2O emissions from open-lot cattle feedlots, which found a wide range of 0.002–4.3 kg N_2O $head^{-1}$ $year^{-1}$ (Waldrip et al., 2016). The authors attributed this wide range of N_2O emissions to differences in pen management, livestock density, animal diet, and environmental conditions (temperature, moisture). The N_2O emissions from our study are in the lower third of reported cattle feedyard emissions, which seems plausible given that the animal diet in our study consisted entirely of savanna vegetation that has a low protein content, subsequently leading to low manure N-content (1.5%) and high C/N ratio (23.6). For comparison, the C/N ratio of manure from cattle in more industrialized livestock production systems ranges from 14 in dairy systems in Austria (Amon et al., 2001) to 17 for beef cattle feedlots in Brazil (Costa et al., 2014), and to about 20 for grazing systems in the UK (Parkinson et al., 2004). In addition, the cattle in our study were of the indigenous *Boran* breed that is more efficient in water and N-retention than high-producing dairy or beef cattle breeds that are raised on N-rich diets and with good water availability (Wassie et al., 2019).

The savanna grassland at our site emitted 0.22 kg N ha^{-1} $year^{-1}$, which is in the same range as reported by others who found N_2O emissions of 0.25 kg N ha^{-1} $year^{-1}$ for a grassland used for cattle and sheep grazing in Inner Mongolia (Yang et al., 2015), or 0.13 kg N ha^{-1} $year^{-1}$ for a grazing land in Taita Taveta County, Southern Kenya (Wachiye et al., 2020). Furthermore, we found an influence of distance to bomas on soil N_2O fluxes, with increasing N_2O fluxes in the vicinity of cattle bomas. Savanna ecosystems are often N-limited and have a tight N cycle, and several other studies have found low N availability and low N_2O fluxes in similar savanna ecosystems (Brümmer et al., 2009; Castaldi et al., 2006; Grover et al., 2012). Consequently, it is plausible that the N input from dung and urine of grazing livestock improved N availability to soil microorganisms in the vicinity of the bomas, and thereby increased N_2O emissions. For the most distant savanna transect point, at 100 m distance from the bomas, the annual mean N_2O flux was 2.5 ± 2.2 µg N m^{-2} h^{-1}, which is in the same range of what was reported for grazing land (1.5 ± 0.4 µg N m^{-2} h^{-1}) in Taita Taveta, Kenya (Wachiye et al., 2020). In addition, there was a positive correlation between soil N_2O flux and soil moisture. Moisture increases the connectivity between soil microorganisms and their substrates, thereby increasing microbial activity (Moyano et al., 2013). Consequently, several studies have reported an increase of soil N_2O flux after rainfall and rewetting events in tropical pastures, particularly after manure deposition (Pelster et al., 2016; Scholes et al., 1997; Wachiye et al., 2020; Zhu et al., 2024). Regarding effects of moisture and seasonality on boma N_2O emissions, N_2O emissions increased in the wet season only in inactive but not in active bomas. This seems plausible as active bomas receive considerable amounts of urine every night, which leaves the manure layer continuously moist and therefore, rainfall events do not trigger additional N_2O pulses. In contrast, inactive bomas dry out quickly under the savanna sun, and rewetting promotes pulses of high N_2O fluxes, as was observed during the rainy season between Oct-Dec 2017 during which the highest N_2O fluxes of the study period were recorded (up to 2120 ± 388 µg N m^{-2} h^{-1} on 17-Oct-2017).

4.2. Methane emissions

As expected, cattle bomas were sources of CH_4 emissions (hypothesis 2), and cumulative CH_4 emissions from bomas were up to 100-times higher than from adjacent savanna soils. The CH_4 emissions from bomas recorded in this study (212 kg C ha^{-1} $year^{-1}$ for active bomas, 153 kg C ha^{-1} $year^{-1}$ for inactive bomas) were higher than emissions recorded from sheepfolds and summer cattle sheds in Inner Mongolia, which ranged from 8 to 93 kg C ha^{-1} $year^{-1}$ (Chen et al., 2022). Calculated on a per-animal basis, cattle bomas in this study emitted 1.72 kg CH_4 $head^{-1}$ $year^{-1}$, which is more than five times higher than values reported for Inner Mongolia (0.31 kg CH_4 $head^{-1}$ $year^{-1}$), where emissions are restricted by cold winters (Chen et al., 2022). Emissions from open feedlots in Southern Idaho (0.04–0.34 kg CH_4 $head^{-1}$ $year^{-1}$), where manure is periodically removed (Leytem et al., 2011) were negligible compared to our findings. In contrast, at our site manure was accumulating over 1–3 months during boma use, after which it was left in the bomas. This is a common scenario for pastoral systems in SSA, where manure is rarely removed from cattle bomas and can accumulate over months and years (Butterbach-Bahl et al., 2020; Marshall et al., 2018). Nevertheless, even though bomas in this study showed higher CH_4 emissions than found for livestock enclosures elsewhere, at the farm scale, enteric CH_4 emissions from the digestive tract of the animals were by far the biggest source of CH_4 (97.6%), while boma manure emissions only contributed about 2.2%. Therefore, efforts to mitigate livestock CH_4 emissions in African pastoral systems should focus on enteric CH_4 emissions, for example by improving productivity per animal to reduce CH_4 emission intensities (emissions per unit of milk or meat).

Considering temporal dynamics, during the wet season active bomas emitted more CH_4 than inactive bomas, where flux rates were close to zero. This partly confirms our second hypothesis that CH_4 emissions from bomas are highest in fresh manure immediately after excretion, when methanogens from the digestive tract are still viable, and then decline when methanogens die off due to O_2 exposure. However, in contrast to our expectations, the highest CH_4 flux of the study (25,200 µg C m^{-2} h^{-1}) was measured in inactive bomas during the dry season. This emission event occurred three weeks after a heavy rainstorm (100 mm precipitation in three days) and shortly after bomas had been abandoned. We assume that it was the combination of recent moisture input from the rainfall event, together with input of viable gut methanogens from the animals not too long ago, and the fact that the bomas were abandoned and the manure layer therefore undisturbed (no mixing via trampling), which led to optimal conditions for methane production (stable, water-saturated conditions and sufficient supply of C and N to enable growth of methanogens) that caused this large CH_4 emission event. This highlights the need for high-frequency measurements (at least once per week, ideally more frequent) and a long-enough study duration (at least one rainy and one wet season, ideally a full year) (Jungbluth et al., 2001) to ensure that such short-lived emission pulses that can dominate the CH_4 balance are captured. In addition, this can be used to reduce manure CH_4 emissions, for example through frequent turning and mixing for aeration, although this may have a stimulating effect on N_2O emissions, (Chadwick et al., 2011), or through regular removal of manure from livestock enclosures.

Considering the influence of cattle bomas on savanna soil CH_4 flux, no effect of distance to bomas was found when calculated over the entire study period. However, when considering only the period during which cattle were present in the area and there was input of fresh excreta from grazing animals, CH_4 fluxes increased in the vicinity (<30 m) of the bomas. Once the cattle left the area, this effect disappeared, likely because CH_4 emissions from excreta deposited on pasture are short-lived in tropical grasslands because dung patches dry out rapidly (Zhu et al., 2021b, 2018).

4.3. Carbon dioxide emissions

Bomas were large sources of CO_2 emissions due to input of manure C and gut microorganisms, which promoted microbial activity and respiration (hypothesis 3). Consequently, active bomas emitted 43.3 Mg C ha^{-1} $year^{-1}$, while inactive bomas emitted only 14.6 Mg C ha^{-1} $year^{-1}$, which was still almost ten-times higher than savanna background emissions (1.9 Mg C ha^{-1} $year^{-1}$). Others found similar magnitudes of CO_2 emissions, for example 17.2 Mg C ha^{-1} $year^{-1}$ for sheep and cattle sheds in Inner Mongolia (Chen et al., 2022), 4.4 Mg C ha^{-1} $year^{-1}$ for grazing land in Taita Taveta, Kenya (Wachiye et al., 2020), and 4–5 Mg C ha^{-1} $year^{-1}$ for average CO_2 emissions from grasslands globally (Raich and Schlesinger, 1992). In this study, CO_2 emissions were highest in active bomas and then decreased after bomas were abandoned. However, rainfall triggered CO_2 pulses 3.5 months after abandonment that reached the same magnitude of CO_2 fluxes as measured in active bomas. This indicates that in abandoned bomas, decomposition and respiration are limited by moisture rather than C availability. This is in line with a previous study from Kenya that found very slow manure decomposition rates in semi-arid rangelands, which was attributed to moisture limitation of organic matter breakdown (Zhu et al., 2020a). In addition, savanna soil respiration increased during the wet season in response to rainfall. This is a common pattern for tropical savannas that are limited by water availability because rainfall increases hydrological connectivity between soil microorganisms and their substrates as stated earlier (Merbold et al., 2009; Moyano et al., 2013), and it also promotes vegetation growth and activity, which has been shown to be another key driver for soil respiration in Kenyan grasslands (Wachiye et al., 2022).

4.4. Methane and nitrous oxide emission factors

In contrast to our expectations, EF_{N2O} and EF_{CH4_VS} for bomas were similar to the IPCC default EFs for feedlots for low-producing non-dairy cattle in warm climates (IPCC, 2019, 2006). This indicates that in absence of country-specific EFs, governments of SSA countries can use feedlot default factors to report N_2O and CH_4 emissions from cattle bomas. Nevertheless, this implies that bomas and similar overnight livestock enclosures need to be captured in the activity data collection for livestock manure management. To our knowledge, SSA countries only report emissions from manure deposited on pasture for their pastoral systems while emissions from bomas are not captured (Graham et al., 2022; Ndambi et al., 2019). This can lead to significant underestimation of manure GHG emissions from SSA, as has also been stated by Butterbach-Bahl et al. (2020) who estimated that active and abandoned bomas from cattle alone contribute 5% to total N_2O emissions from the African continent. Considering that bomas from other livestock, particularly sheep, goats, and camels, are also common in pastoral systems and can be GHG emission hotspots (Zhu et al., 2024), and that livestock numbers in SSA are growing, it is critical that active and inactive bomas be included in national GHG inventories to reduce current uncertainties in anthropogenic GHG emission sources and to better explain rising atmospheric N_2O and CH_4 concentrations (Jackson et al., 2020; Wells et al., 2018). This can be achieved by including bomas and similar livestock enclosures as manure management category in the animal activity data collection for GHG inventories (Leitner et al., 2020), or by using novel techniques such as satellite-based remote sensing to map bomas from space (Vrieling et al., 2022). In addition, we want to point out that in the present study, boma EFs were calculated only for the first year after abandonment, but abandoned cattle bomas can emit N_2O for years to decades. Butterbach-Bahl et al. (2020) estimated that an additional 1.34%N (range of 0.90–2.56%) is emitted as N_2O over 40 years after boma abandonment. In comparison, the EF_{N2O} in our study is 2.43 ± 0.42%N for the first year after abandonment alone. Assuming that bomas remain N_2O emission sources for at least 40 years, this would result in a combined EF_{N2O} of 3.74%N, almost twice as high as the IPCC default for feedlots (2%N), which assumes regular manure removal and only accounts for the year when feedlots are in use and does not consider emissions after abandonment (IPCC, 2019).

Regarding the limitations of our study, we wish to highlight that boma management across SSA varies considerably by ethnic group and accessibility. In addition, the number of animals in a boma, the quality of the feces, or the number of days and seasons that bomas are used vary regionally (see e.g. Butterbach-Bahl et al., 2020). Boma management can only be addressed through targeted surveys combined with remote sensing analysis (e.g. Vrieling et al., 2022), as very little is known about the movement patterns of bomas across the landscape.

One way to mitigate N_2O emissions from livestock bomas in sub-Saharan Africa could be to regularly remove manure from bomas (Costa et al., 2014; Petersen et al., 2013). The collected boma manure can be used as fertilizer to replenish nutrients removed by grazing livestock in the adjacent grasslands. Previous research from Kenya reported a net nutrient transfer from grasslands to bomas, and these locations have been suggested to be hotspots for N loss from the rangeland, causing a negative N balance (Carbonell et al., 2021). Thus, current rangeland management risks degradation and nutrient depletion of soils, reducing rangeland productivity and causing long-term loss of soil organic matter. Similar findings have been reported from Western Africa, where livestock are left to graze on grasslands and are then penned on croplands overnight for manure input and soil fertilization, leading to a net nutrient transfer from grassland to cropland (Powell et al., 2004). As long as livestock densities are relatively low and pastoralists are migrating with their animals across vast areas, grasslands can cope with this nutrient loss, as it resembles the migration of wild herbivores that have dominated landscape nutrient transfer for millennia (Macharia et al., 2012; Marshall et al., 2018). However, recent developments, such as conflict-related restriction of migration routes (Kaimba et al., 2011), reduced access to traditional grazing grounds due to land-use change and grassland conversion (Tyrrell et al., 2022; Wafula et al., 2022), increasing frequency and severity of droughts (Descheemaeker et al., 2016), and increasing sedentarization and urbanization of pastoralists (Hauck and Rubenstein, 2017) are leading to locally increased livestock densities (Augustine, 2003; Edwards et al., 2022). Reduced pastoralist mobility leads to longer boma use times (Lamprey and Reid, 2004), with larger quantities of manure accumulating in the bomas, and higher grazing pressure and nutrient removal from the surrounding grassland. This likely leads to higher N_2O emissions and other N losses (e.g., via ammonia volatilization and NO_3^- leaching) from bomas, and at the same time reduces N reservoirs in the surrounding soils. To combat these developments, an integrated landscape-scale approach considering various stakeholders and institutions is required, the description of which is beyond the scope of this study. However, from a nutrient cycling perspective, the aim should be to return as much N and other nutrients from the bomas back to the surrounding grassland, for example by spreading boma manure on the grassland or by using short-rotation bomas (Carbonell et al., 2021; Porensky and Veblen, 2015), or to use boma manure as fertilizer for alternative feed production to supplement the grass-based livestock diet.

5. Conclusions

This is the first study to present a full year of GHG flux measurements from cattle bomas in SSA. Bomas are significant sources of N_2O, CH_4, and CO_2, with fluxes several orders of magnitude higher than compared to background savanna soil emissions even after boma abandonment. At the farm-scale, CH_4 emissions from bomas only contributed little compared to enteric CH_4 emissions, but boma N_2O emissions contributed over 32% to farm-scale N_2O emissions. This corroborates the importance of bomas for livestock GHG budgets in SSA and calls for the inclusion of bomas and other similar livestock enclosures as a manure management practice in the activity data collection for national GHG inventories. Furthermore, to improve the current estimates of GHG emissions from bomas, a combined measuring and modelling approach that includes remote sensing is required in order to enhance our understanding of boma numbers, distribution, and movement. To mitigate boma N_2O emissions, regular removal of boma manure or frequent boma relocation are suggested. This can potentially improve grassland productivity and drought resilience by ensuring that nutrients that are removed by grazing animals are returned to the soil, thereby preventing soil nutrient mining and soil degradation. Finally, it should be emphasized that pastoralists in SSA use bomas not only for cattle but also for sheep, goats, and camels; therefore, future studies should assess GHG emissions and N losses from bomas of other livestock species while also considering other environmental dimensions (e.g., effects on biodiversity).

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CRediT authorship contribution statement

Klaus Butterbach-Bahl: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Paul Mutuo:** Investigation. **Lutz Merbold:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Victoria Carbonell:** Writing – original draft, Investigation. **Sonja Maria Leitner:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Yuhao Zhu:** Writing – review & editing. **Rangarirayi Lucia Mhindu:** Investigation.

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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.108980.

References

Aguilar, O.A., Maghirang, R., Rice, C.W., Trabue, S.L., Erickson, L.E., 2014. Nitrous oxide fluxes from a commercial beef cattle feedlot in Kansas. Air, Soil Water Res. 7, 35–45. https://doi.org/10.4137/ASWR.S12841/ASSET/IMAGES/LARGE/10.4137_ASWR.S12841-FIG8.JPEG.

Amon, B., Amon, T., Boxberger, J., Alt, C., 2001. Emissions of NH3, N2O and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutr. Cycl. Agroecosyst 60, 103–113. https://doi.org/10.1023/A:1012649028772/METRICS.

Arias-Navarro, C., Díaz-Pinés, E., Kiese, R., Rosenstock, T.S., Rufino, M.C., Stern, D., Neufeldt, H., Verchot, L. v, Butterbach-Bahl, K., 2013. Gas pooling: A sampling technique to overcome spatial heterogeneity of soil carbon dioxide and nitrous oxide fluxes. Soil Biol. Biochem 67, 20–23. https://doi.org/10.1016/j.soilbio.2013.08.011.

Augustine, D.J., 2003. Long-term, livestock-mediated redistribution of nitrogen and phosphorus in an East African savanna. J. Appl. Ecol. 40, 137–149. https://doi.org/10.1046/j.1365-2664.2003.00778.x.

Barrett, C.B., Chabari, F., Bailey, D., Little, P.D., Coppock, D.L., 2003. Livestock pricing in the Northern Kenyan rangelands. J. Afr. Econ. 12, 127–155.

Brümmer, C., Brüggemann, N., Butterbach-Bahl, K., Falk, U., Szarzynski, J., Vielhauer, K., Wassmann, R., Papen, H., 2008. Soil-atmosphere exchange of N2O and NO in near-natural savanna and agricultural land in Burkina Faso (W. Africa). Ecosystems 11, 582–600. https://doi.org/10.1007/s10021-008-9144-1.

Brümmer, C., Papen, H., Wassmann, R., Brüggemann, N., 2009. Fluxes of CH4 and CO2 from soil and termite mounds in south Sudanian savanna of Burkina Faso (West Africa). Glob. Biogeochem. Cycles 23. https://doi.org/10.1029/2008GB003237.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, 20130122–20130122 Philos. Trans. R. Soc. B: Biol. Sci. 368. https://doi.org/10.1098/rstb.2013.0122.

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.

Carbonell, V., Merbold, L., Díaz-Pinés, E., Dowling, T.P.F., Butterbach-Bahl, K., 2021. Nitrogen cycling in pastoral livestock systems in Sub-Saharan Africa: knowns and unknowns. Ecol. Appl. 31 https://doi.org/10.1002/eap.2368.

Castaldi, S., Ermice, A., Strumia, S., 2006. Fluxes of N2O and CH4 from soils of savannas and seasonally-dry ecosystems. J. Biogeogr. 33, 401–415. https://doi.org/10.1111/J.1365-2699.2005.01447.X.

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., Misselbrook, T., 2011. Manure management: Implications for greenhouse gas emissions. Anim. Feed Sci. Technol. 166–167, 514–531. https://doi.org/10.1016/j.anifeedsci.2011.04.036.

Chadwick, D.R., 2005. Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: Effect of compaction and covering. Atmos. Environ. 39, 787–799. https://doi.org/10.1016/j.atmosenv.2004.10.012.

Chen, H., Li, S., Zheng, X., Liu, C., Kuzyakov, Y., 2022. Annual greenhouse gas emissions from sheepfolds and cattle sheds. Soil Use Manag 38, 369–380. https://doi.org/10.1111/sum.12735.

Chen, W., Wolf, B., Brüggemann, N., Butterbach-Bahl, K., Zheng, X., 2011. Annual emissions of greenhouse gases from sheepfolds in Inner Mongolia. Plant Soil 340, 291–301. https://doi.org/10.1007/S11104-010-0367-5/METRICS.

Costa, C., Li, C., Cerri, C.E.P., Cerri, C.C., 2014. Measuring and modeling nitrous oxide and methane emissions from beef cattle feedlot manure management: First assessments under Brazilian condition. J. Environ. Sci. Health, Part B 49, 696–711. https://doi.org/10.1080/03601234.2014.922856.

Descheemaeker, K., Oosting, S.J., Homann-Kee Tui, S., Masikati, P., Falconnier, G.N., Giller, K.E., 2016. Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: A call for integrated impact assessments. Reg. Environ. Change 16, 2331–2343. https://doi.org/10.1007/s10113-016-0957-8.

Edwards, P., Cech, P., Sitters, J., Olde Venterink, H., 2022. Long-Term Effects of Cattle Ranching on Soil Nitrogen and Phosphorus Balances in a Savanna Ecosystem. Rangel. Ecol. Manag 84, 54–62. https://doi.org/10.1016/J.RAMA.2022.05.006.

FAO, 2020. Emissions due to agriculture. Global, regional and country trends 2000-2018. FAOSTAT Analytical Brief 18.

FAO, 2021. The share of agri-food systems in total greenhouse gas emissions. Global, regional and country trends 1990-2019. FAOSTAT Analytical Brief 31.

Goopy, J.P., Onyango, A.A., Dickhoefer, U., Butterbach-Bahl, K., 2018. A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – Results for Nyando, Western Kenya. Agric. Syst. 161, 72–80. https://doi.org/10.1016/j.agsy.2017.12.004.

Graham, M.W., Butterbach-Bahl, K., du Doit, C.J.L., Korir, D., Leitner, S., Merbold, L., Mwape, A., Ndung'u, P.W., Pelster, D.E., Rufino, M.C., van der Weerden, T., Wilkes, A., Arndt, C., 2022. Research Progress on Greenhouse Gas Emissions From Livestock in Sub-Saharan Africa Falls Short of National Inventory Ambitions. Front. Soil Sci. 2 https://doi.org/10.3389/fsoil.2022.927452.

Grover, S.P.P., Livesley, S.J., Hutley, L.B., Jamali, H., Fest, B., Beringer, J., Butterbach-Bahl, K., Arndt, S.K., 2012. Land use change and the impact on greenhouse gas exchange in north Australian savanna soils. Biogeosciences 9, 423–437. https://doi.org/10.5194/BG-9-423-2012.

Hauck, S., Rubenstein, D.I., 2017. Pastoralist societies in flux: A conceptual framework analysis of herding and land use among the Mukugodo Maasai of Kenya. Pastoralism 7, 18. https://doi.org/10.1186/s13570-017-0090-4.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110, 20888–20893. https://doi.org/10.1073/PNAS.1308149110.
ILRI, IUCN, FAO, WWF, UNEP, ILC, 2021. Rangelands Atlas. ILRI, Nairobi.
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 10: Emissions from livestock and manure management Volume 4.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, USA.
IPCC, 2019. Chapter 10: Emissions from livestock and manure management, in: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
Jackson, R.B., Saunois, M., Bousquet, P., Canadell, J.G., Poulter, B., Stavert, A.R., Bergamaschi, P., Niwa, Y., Segers, A., Tsuruta, A., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environ. Res. Lett. 15, 071002 https://doi.org/10.1088/1748-9326/AB9ED2.
Jungbluth, T., Hartung, E., Brose, G., 2001. Greenhouse gas emissions from animal houses and manure stores. Nutr. Cycl. Agroecosyst 60, 133–145. https://doi.org/10.1023/A:1012621627268/METRICS.
Kaimba, G.K., Njehia, B.K., Guliye, A.Y., 2011. Effects of cattle rustling and household characteristics on migration decisions and herd size amongst pastoralists in Baringo District, Kenya. Pastoralism 1, 18. https://doi.org/10.1186/2041-7136-1-18.
Korir, D., Marquardt, S., Eckard, R., Sanchez, A., Dickhoefer, U., Merbold, L., Butterbach-Bahl, K., Jones, C., Robertson-Dean, M., Goopy, J.P., 2022. Weight gain and enteric methane production of cattle fed on tropical grasses. Anim. Prod. Sci. https://doi.org/10.1071/AN21327.
Lamprey, R.H., Reid, R.S., 2004. Expansion of human settlement in Kenya's Maasai Mara: What future for pastoralism and wildlife? J. Biogeogr. 31, 997–1032. https://doi.org/10.1111/j.1365-2699.2004.01062.x.
Latino, L.R., Pica-Ciamarra, U., Wisser, D., 2020. Africa: The livestock revolution urbanizes. Glob. Food Secur. *26*, 100399 https://doi.org/10.1016/J.GFS.2020.100399.
Leitner, S., Pelster, D.E., Owino, J.O., Marquardt, S., Merbold, L., 2020. Protocol for generating region-specific Tier 2 emission factors for methane (CH4) and nitrous oxide (N2O) emissions from cattle manure. International Livestock Research Institute.
Leitner, S., Ring, D., Wanyama, G.N., Korir, D., Pelster, D.E., Goopy, J.P., Butterbach-Bahl, K., Merbold, L., 2021. Effect of feeding practices and manure quality on CH4 and N2O emissions from uncovered cattle manure heaps in Kenya. Waste Manag. 126, 209–220. https://doi.org/10.1016/j.wasman.2021.03.014.
Lenth, R.V., 2023. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.8.7, ⟨https://CRAN.R-project.org/package=emmeans⟩.
Leytem, A.B., Dungan, R.S., Bjorneberg, D.L., Koehn, A.C., 2011. Emissions of Ammonia, Methane, Carbon Dioxide, and Nitrous Oxide from Dairy Cattle Housing and Manure Management Systems. J. Environ. Qual. 40, 1383–1394. https://doi.org/10.2134/jeq2009.0515.
MacCarthy, N., 2000. Property rights, risk, and livestock development in Africa. IFPRI.
Macharia, A.N., Uno, K.T., Cerling, T.E., Brown, F.H., 2012. Isotopically distinct modern carbonates in abandoned livestock corrals in northern Kenya. J. Archaeol. Sci. 39, 2198–2205. https://doi.org/10.1016/J.JAS.2012.02.005.
Maeda, K., Toyoda, S., Shimojima, R., Osada, T., Hanajima, D., Morioka, R., Yoshida, N., 2010. Source of nitrous oxide emissions during the cow manure composting process as revealed by isotopomer analysis of and amoa abundance in betaproteobacterial ammonia-oxidizing bacteria. Appl. Environ. Microbiol 76, 1555–1562. https://doi.org/10.1128/AEM.01394-09/SUPPL_FILE/091208_AEM_2ND_REVISION_TABLE_S1.DOC.
Marshall, F., Reid, R.E.B., Goldstein, S., Storozum, M., Wreschnig, A., Hu, L., Kiura, P., Shahack-Gross, R., Ambrose, S.H., 2018. Ancient herders enriched and restructured African grasslands. Nature 561, 387–390. https://doi.org/10.1038/s41586-018-0456-9.
Merbold, L., Ardö, J., Arneth, A., Scholes, R.J., Nouvellon, Y., De Grandcourt, A., Archibald, S., Bonnefond, J.M., Boulain, N., Brueggemann, N., Bruemmer, C., Cappelaere, B., Ceschia, E., El-Khidir, H.A.M., El-Tahir, B.A., Falk, U., Lloyd, J., Kergoat, L., Le Dantec, V., Mougin, E., Muchinda, M., Mukelabai, M.M., Ramier, D., Roupsard, O., Timouk, F., Veenendaal, E.M., Kutsch, W.L., 2009. Precipitation as driver of carbon fluxes in 11 African ecosystems. Biogeosciences 6, 1027–1041. https://doi.org/10.5194/BG-6-1027-2009.
Metcalfe, D.B., Meir, P., Aragão, L.E.O.C., Malhi, Y., da Costa, A.C.L., Braga, A., Gonçalves, P.H.L., de Athaydes, J., de Almeida, S.S., Williams, M., 2007. Factors controlling spatio-temporal variation in carbon dioxide efflux from surface litter, roots, and soil organic matter at four rain forest sites in the eastern Amazon. J. Geophys Res Biogeosci 112. https://doi.org/10.1029/2007JG000443.
Mgalula, M.E., Wasonga, O.V., Hülsebusch, C., Richter, U., Hensel, O., 2021. Greenhouse gas emissions and carbon sink potential in Eastern Africa rangeland ecosystems: A review, 2021 11:1 11, 1–17 Pastoralism. https://doi.org/10.1186/S13570-021-00201-9.
Moritz, S., Bartz-Beielstein, T., 2017. imputeTS: Time Series Missing Value Imputation in R. R. J. 9, 207–218. https://doi.org/10.32614/RJ-2017-009.
Moyano, F.E., Manzoni, S., Chenu, C., 2013. Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. Soil Biol. Biochem. https://doi.org/10.1016/j.soilbio.2013.01.002.
Muthoka, J.M., Antonarakis, A.S., Vrieling, A., Fava, F., Salakpi, E.E., Rowhani, P., 2022. Assessing drivers of intra-seasonal grassland dynamics in a Kenyan savannah using digital repeat photography. Ecol. Indic. 142, 109223 https://doi.org/10.1016/J.ECOLIND.2022.109223.
Mwai, O., Hanotte, O., Kwon, Y.J., Cho, S., 2015. Invited review - African indigenous cattle: Unique genetic resources in a rapidly changing world. Asian-Austral J. Anim. Sci. https://doi.org/10.5713/ajas.15.0002R.
Ndambi, O.A., Pelster, D.E., Owino, J.O., de Buisonjé, F., Vellinga, T., 2019. Manure Management Practices and Policies in Sub-Saharan Africa: Implications on Manure Quality as a Fertilizer. Front Sustain Food Syst. 3, 1–14. https://doi.org/10.3389/fsufs.2019.00029.
Ndung'u, P.W., Bebe, B.O., Ondiek, J.O., Butterbach-Bahl, K., Merbold, L., Goopy, J.P., 2018. Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: Livestock systems of Nandi County, Kenya. Anim. Prod. Sci. https://doi.org/10.1071/AN17809.
Ogutu, J.O., Piepho, H.P., Said, M.Y., Ojwang, G.O., Njino, L.W., Kifugo, S.C., Wargute, P.W., 2016. Extreme wildlife declines and concurrent increase in livestock numbers in Kenya: What are the causes? PLoS One 11. https://doi.org/10.1371/journal.pone.0163249.
Owen, J.J., Silver, W.L., 2015. Greenhouse gas emissions from dairy manure management: A review of field-based studies. Glob. Chang Biol. 21, 550–565. https://doi.org/10.1111/gcb.12687.
Parkinson, R., Gibbs, P., Burchett, S., Misselbrook, T., 2004. Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. Bioresour. Technol. 91, 171–178. https://doi.org/10.1016/S0960-8524(03)00174-3.
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. https://doi.org/10.2134/jeq2016.02.0050.
Petersen, S.O., Stamatiadis, S., Christofides, C., 2004. Short-term nitrous oxide emissions from pasture soil as influenced by urea level and soil nitrate. Plant Soil 267, 117–127. https://doi.org/10.1007/S11104-005-4688-8/METRICS.
Petersen, S.O., Blanchard, M., Chadwick, D., Del Prado, A., Edouard, N., Mosquera, J., Sommer, S.G., 2013. Manure management for greenhouse gas mitigation. Animal 7, 266–282. https://doi.org/10.1017/S1751731113000736.
Porensky, L.M., Veblen, K.E., 2015. Generation of ecosystem hotspots using short-term cattle corrals in an African savanna. Rangel. Ecol. Manag 68, 131–141. https://doi.org/10.1016/j.rama.2015.01.002.
Powell, J.M., Pearson, R.A., Hiernaux, P.H., 2004. Crop-livestock interactions in the West African drylands. Agron. J. 96, 469–483. https://doi.org/10.2134/agronj2004.4690.
R Core Team, 2019. R: A Language and Environment for Statistical Computing.
Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus, Ser. B 44, 81–99. https://doi.org/10.3402/TELLUSB.V44I2.15428.
Rochette, P., 2011. Towards a standard non-steady-state chamber methodology for measuring soil N2O emissions. Anim. Feed Sci. Technol. 166–167, 141–146. https://doi.org/10.1016/j.anifeedsci.2011.04.063.
Scholes, M.C., Martin, R., Scholes, R.J., Parsons, D., Winstead, E., 1997. NO and N2O emissions from savanna soils following the first simulated rains of the season. Nutr. Cycl. Agroecosyst 48, 115–122. https://doi.org/10.1023/A:1009781420199/METRICS.
Thornton, P.K., 2010. Livestock production: Recent trends, future prospects. Philos. Trans. R. Soc. B: Biol. Sci. 365 (1554), 2853–2867. https://doi.org/10.1098/rstb.2010.0134.
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., Arneth, 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.
Tyrrell, P., Buitenwerf, R., Brehony, P., Løvschal, M., Wall, J., Russell, S., Svenning, J.-C., Macdonald, D.W., du Toit, J.T., Kamanga, J., 2022. Wide-scale subdivision and fencing of southern Kenyan rangelands jeopardizes biodiversity conservation and pastoral livelihoods: Demonstration of utility of open-access landDX database. Front. Conserv. Sci. 0, 104. https://doi.org/10.3389/FCOSC.2022.889501.
Vrieling, A., Fava, F., Leitner, S., Merbold, L., Cheng, Y., Nakalema, T., Groen, T., Butterbach-Bahl, K., 2022. Identification of temporary livestock enclosures in Kenya from multi-temporal PlanetScope imagery. Remote Sens Environ. 279 https://doi.org/10.1016/j.rse.2022.113110.
Wachiye, S., Merbold, L., Vesala, T., Rinne, J., Räsänen, M., Leitner, S., Pellikka, P., 2020. Soil greenhouse gas emissions under different land-use types in savanna ecosystems of Kenya. Biogeosciences 17, 2149–2167. https://doi.org/10.5194/bg-17-2149-2020.
Wachiye, S., Pellikka, P., Rinne, J., Heiskanen, J., Abwanda, S., Merbold, L., 2022. Effects of livestock and wildlife grazing intensity on soil carbon dioxide flux in the savanna grassland of Kenya. Agric. Ecosyst. Environ. 325 https://doi.org/10.1016/j.agee.2021.107713.
Wafula, W.M., Wasonga, O.V., Koech, O.K., Kibet, S., 2022. Factors influencing migration and settlement of pastoralists in Nairobi City. Kenya Pastor. 12, 1–14. https://doi.org/10.1186/S13570-021-00204-6/TABLES/5.
Waldrip, H.M., Todd, R.W., Parker, D.B., Cole, N.A., Rotz, C.A., Casey, K.D., 2016. Nitrous Oxide Emissions from Open-Lot Cattle Feedyards: A Review. J. Environ. Qual. 45, 1797–1811. https://doi.org/10.2134/JEQ2016.04.0140.

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.

Wells, K.C., Millet, D.B., Bousserez, N., Henze, D.K., Griffis, T.J., Chaliyakunnel, S., Dlugokencky, E.J., Saikawa, E., Xiang, G., Prinn, R.G., O'Doherty, S., Young, D., Weiss, R.F., Dutton, G.S., Elkins, J.W., Krummel, P.B., Langenfelds, R., Paul Steele, L., 2018. Top-down constraints on global N2O emissions at optimal resolution: Application of a new dimension reduction technique. Atmos. Chem. Phys. 18, 735–756. https://doi.org/10.5194/ACP-18-735-2018.

Wolz, K., Leitner, S., Merbold, L., Wolf, B., Mauder, M., 2022. Enteric methane emission estimates for Kenyan cattle in a nighttime enclosure using a backward Lagrangian Stochastic dispersion technique. Theor. Appl. Clim. 147, 1091–1103. https://doi.org/10.1007/s00704-021-03868-7.

Yang, X., Chen, H., Gong, Y., Zheng, X., Fan, M., Kuzyakov, Y., 2015. Nitrous oxide emissions from an agro-pastoral ecotone of northern China depending on land uses. Agric. Ecosyst. Environ. 213, 241–251. https://doi.org/10.1016/J.AGEE.2015.08.011.

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., Pelster, D.E., Okoma, S.A., Ngetich, F., Onyango, A.A., Pellikka, P., Butterbach-Bahl, K., 2020a. The effects of climate on decomposition of cattle, sheep and goat manure in Kenyan tropical pastures. Plant Soil 451, 325–343. https://doi.org/10.1007/s11104-020-04528-x.

Zhu, Y., Merbold, L., Leitner, S., Xia, L., Pelster, D.E., Diaz-Pines, E., Abwanda, S., Mutuo, P.M., Butterbach-Bahl, K., 2020b. 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., 2021b. Interactive effects of dung deposited onto urine patches on greenhouse gas fluxes from tropical pastures in Kenya. Sci. Total Environ. 761 https://doi.org/10.1016/j.scitotenv.2020.143184.

Zhu, Y., Butterbach-Bahl, K., Merbold, L., Leitner, S., Pelster, D.E., 2021a. Nitrous oxide emission factors for cattle dung and urine deposited onto tropical pastures: A review of field-based studies. Agric. Ecosyst. Environ. 322 https://doi.org/10.1016/j.agee.2021.107637.

Zhu, Y., Butterbach-Bahl, K., Merbold, L., Oduor, C.O., Gakige, J.K., Mwangi, P., Leitner, S.M., 2024. Greenhouse gas emissions from sheep excreta deposited onto tropical pastures in Kenya. Agric. Ecosyst. Environ. 359, 108724 https://doi.org/10.1016/J.AGEE.2023.108724.