Odessa centre | Pastoralism Research, Policy and Practice

TYPE Original Research
PUBLISHED 02 July 2025
DOI 10.3389/past.2025.14566

Check for updates

OPEN ACCESS

EDITED BY
Jonathan Davies,
United Nations, United States

*CORRESPONDENCE
C. Arndt,
claudia.arndt@cgiar.org

†PRESENT ADDRESSES
P. W. Ndungu,
Food and Agricultural Organization of the United Nations, Animal Production and Health Division, Rome, Italy

RECEIVED 28 February 2025
ACCEPTED 16 June 2025
PUBLISHED 02 July 2025

CITATION
Gurmu EB, Kiprotich LE, Kagai JG, Solomon A, Leitner S, Marquardt S, Merbold L, Ndungu PW and Arndt C (2025) Beyond default estimates: developing system-specific Tier 2 enteric methane emission factors for rangeland cattle in Kenya. *Pastoralism* 15:14566.
doi: 10.3389/past.2025.14566

Beyond default estimates: developing system-specific Tier 2 enteric methane emission factors for rangeland cattle in Kenya

E. B. Gurmu[1,2], L. E. Kiprotich[1], J. G. Kagai[1], A. Solomon[3], S. Leitner[1], S. Marquardt[1], L. Merbold[4], P. W. Ndungu[1†] and C. Arndt[1]*

[1]International Livestock Research Institute (ILRI), Mazingira Center, Nairobi, Kenya, [2]College of Veterinary Sciences, Mekelle University, Mekelle, Ethiopia, [3]College of Dryland Agriculture, Jigjiga University, Jigjiga, Ethiopia, [4]Integrative Agroecology Group, Research Division Agroecology and Environment, Agroscope, Zurich, Switzerland

Livestock production in Kenya is a significant source of greenhouse gas emissions, particularly methane (CH_4) from enteric fermentation. The objective of the study was to estimate enteric methane (CH_4) emission factors (EFs, kg CH_4/head/year) for rangeland cattle in Kenya. The study utilized the Intergovernmental Panel on Climate Change (IPCC) Tier 2 method, incorporating animal characteristics, performance data, and diet digestibility. Data were obtained from 1,486 cattle across three locations in Kenya's pastoral areas: Kapiti Research Station and Wildlife Conservancy (815 cattle), Olkirimatian Community Ranch (347 cattle), and Shompole Community Ranch (324 cattle) all located in southern Kenya. Animal activity data were collected for four seasons during 1 year at Kapiti, and one dry and one wet season in Olkirimatian and Shompole. The EFs were estimated for wet and dry seasons, allowing the calculation of mean annual EFs. The EFs were calculated for the different cattle categories: adult females and males (≥3 years), young males and females (1–3 years) and calves (<1 year). The results revealed significant differences in herd composition, live weight (LW), weight gains, milk yield, and digestible energy (DE) of pasture among the locations, all of which influence CH_4 emissions. LW varied among the three locations due to differences in breed between sites and varied substantially compared to Tier 1 assumptions, and DE differed significantly across sites (54.5%–66.4%), despite the Tier 1 approach assuming a fixed DE value for pasture (58%). There was a significant difference ($p < 0.05$) in the herd level EF of all cattle categories: Kapiti (64 ± 0.9 kg CH_4/head/year), followed by Olkirimatian (52 ± 1.2 kg CH_4/head/year) and Shompole (42 ± 1.0 kg CH_4/head/year). A comparison of the estimated herd level Tier 2 EFs with computed herd level Tier 1 values revealed that Kapiti exhibited 18% higher mean Tier 2 EFs, while it was lower by 7% and 28% in Olkirimatian and Shompole, respectively. These findings highlight the need for system-specific national EFs that better capture the diversity of production systems and breed differences. Policymakers and researchers should revise IPCC default values to incorporate breed-specific factors within systems.

KEYWORDS

IPCC, pastoral systems, semi-arid environments, ranching, southern Kenya

Introduction

Livestock production is a major agricultural activity in Kenya, contributing 30 percent of the agricultural GDP and 12 percent to the national GDP (Thornton et al., 2019). However, the sector also significantly contributes to greenhouse gas (GHG) emissions, primarily through methane (CH_4) emissions from enteric fermentation (Ortiz-Gonzalo et al., 2017). Methane is a potent GHG with a global warming potential over 80 and 28 times greater than carbon dioxide on a 20- and 100-year timescale, respectively, making it a significant contributor to global warming and climate change (IPCC, 2021). Some estimates show that enteric emissions accounted for 98% of livestock management-associated GHGs in Kenya's livestock production system (Mwaura et al., 2019).

Kenya's diverse agroecological zones support a wide range of livestock production systems, including mixed-crop livestock system, traditional pastoral systems and emerging ranching systems (Kosgey et al., 2008; Njarui et al., 2016; Ngetich et al., 2023). Traditional pastoral systems are characterized by extensive grazing on natural grasslands, with limited external feed inputs and a focus on animal mobility to exploit seasonal variations in forage availability (Lutta et al., 2021). In contrast, ranching systems can provide a more controlled approach to livestock management, aiming to ensure adequate nutrition and manage grazing pressure (Yurco, 2017; Ndiritu, 2021). However, evidence shows that overgrazing in rangelands is often a consequence of constraints on pastoralist mobility—such as land privatization and restricted movement—rather than an inherent outcome of pastoralism itself. When mobility is maintained, pastoralist systems have been demonstrated to be among the most sustainable for managing rangeland resources (Oba, 2011).

Rural populations in the arid and semi-arid lands (ASALs) are predominantly engaged in traditional pastoralism centered on the raising of cattle and other livestock on rangelands (Karanja Ng'ang'a et al., 2016). Traditional pastoralism is explicitly adapted to cope with the seasonality and spatial variability of forage, relying on herd mobility to access dispersed and fluctuating grazing resources (Oba, 2011). This mobility is a key resilience mechanism, allowing pastoralists to buffer against drought and resource scarcity. Sedentarization of pastoralists is not a response to seasonality but rather results from external pressures such as disruption of mobility routes, land fragmentation, and limited-service provision to mobile communities. Such loss of mobility can reduce the system's capacity to respond to environmental variability, potentially increasing vulnerability to feed shortages and land degradation (WISP, 2008; Yurco, 2017; Ndiritu, 2021).

Studying greenhouse gas emissions in pastoralist systems is particularly relevant because these systems are frequently reported to have higher emission intensities per unit of product compared to other livestock systems, largely due to low-input management and variable feed quality (Gerber et al., 2013). However, there is considerable debate about these estimates, as conventional methods may not fully capture the unique ecological dynamics and carbon offsets provided by pastoral rangelands (GIZ, 2022). Accurate estimation of enteric CH_4 emissions is essential for understanding the environmental footprint of livestock production for national GHG livestock inventory accounting and developing effective strategies to mitigate enteric emissions (Gerber et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for estimating GHG emissions, categorizing the methodologies into different tiers based on data availability and specificity. Tier 1 methods rely on one default emission factor for each animal category for Africa, while Tier 2 approaches aim to generate more detailed, site-specific estimates by using local livestock production data such as animal weight, diet, breed, and herd composition.

Rangeland and pastoral systems in Kenya are characterized by high variability in forage availability, traditional mobility strategies, and increasing exposure to climate and policy pressures. Understanding CH_4 emissions in this context is crucial for developing mitigation strategies that are both scientifically robust and socially equitable. Most existing research in Kenya have estimated Tier 2 enteric CH_4 emission factors (EFs) for mixed-crop livestock systems and reported that the IPCC Tier 1 method tends to overestimate emissions from livestock systems in the country (Goopy et al., 2018; Ndung'u et al., 2020; Goopy et al., 2021; Ndung'u et al., 2022). Furthermore, the studies have employed region-specific methods based on locally developed Tier 2 methods at the International Livestock Research Institute, referred to as the "CSIRO" model and not the official IPCC Tier 2 guidelines. By focusing on three distinct rangeland sites, with different breed composition and management practices, this study aims to provide emission factors that are more representative of the diversity and challenges faced by Kenya's rangeland system.

The objective of this study was to estimate enteric CH_4 emissions from two rangeland systems in three locations in

Southern Kenya: Kapiti Research Station and Wildlife Conservancy Shompole and Olkirimatian community ranches. By adopting the IPCC Tier 2 method, which incorporates animal energy requirements derived from animal characteristics, performance, diet quality and herd structure, the study aimed to generate accurate and location-specific enteric CH_4 emission factors for rangeland systems. This study also considers the net energy mobilized due to weight loss, which is not accounted in the recent IPCC guidelines.

While this study focuses on ranching systems, it is important to recognize that these systems exist along a continuum between traditional pastoralism and more controlled ranching. In Kenya, many rangeland areas are managed by pastoralist communities, and the management practices observed in Olkirimatian and Shompole reflect adaptations of traditional pastoral strategies, such as seasonal mobility and communal land use. By comparing these with the more structured management at Kapiti Ranch, our study offers insights into how different rangeland management approaches—ranging from pastoralist to ranching—affect methane emissions. This comparison is particularly relevant for informing climate change mitigation strategies in pastoral regions, where livestock production remains a critical livelihood and emissions source. The study hypothesized that enteric emission factors of cattle vary among different rangeland systems in Southern Kenya.

Materials and methods

Selection of study sites

This study was conducted in three specific locations in southern Kenya-Kapiti Research Station and Wildlife Conservancy (1.63397°S, 37.1476°E), Olkirimatian Community Ranch (1.8997˚S, 36.3010˚E), and Shompole Community Ranch (2.0910˚S, 36.1179˚E)-representing rangeland cattle systems in semi-arid environments. Kapiti Research Station and Wildlife Conservancy is owned by the International Research Institute (ILRI). The other two ranches are located in Magadi where pastoralism is the predominant livestock production system.

Kapiti Research Station and Wildlife Conservancy is located in the semi-arid drylands in southern Kenya with an average rainfall of 550 mm per year (Carbonell et al., 2021). It is found at an elevation of 1,650–1,900 m above sea level and covers an area of 13,279 ha in Machakos County. It is an extensive ranching system where livestock stays in the grasslands all day.

The two community ranches in Magadi (Shompole and Olkirimatian) are Maasai communities in a pastoral rangeland in the south of Kenya (Kajiado county) with average elevation of 641 m above sea level. Magadi is an area abundant in mostly untouched natural resources, encompassing forests, grassy plains, the Ewaso Nyiro River, and unique volcanic landscapes, which include the alkaline Lake Magadi and the Nguruman Escarpment. Olkirimatian community ranch occupies an extensive area of 24,000 ha. Shompole community ranch covers 62,700 ha. In both ranches, the land is owned by pastoralists who have designated settlement and farming area (Ontiri and Robinson, 2018). The animals are managed in paddocks. The paddocks are communally owned by group ranch members, who enforce grazing rules and sustainable use of the paddocks. The community uses traditional bylaws and grazing committees to regulate access to paddocks, including restrictions on grazing certain areas to allow pasture regeneration, especially during dry seasons.

The cattle in Kapiti Research Station and Wildlife Conservancy were either typical Boran breeds or a crossbreed of Holstein and Boran. This cross is not typical of ranch systems. Shompole Ranch had exclusively crossbreeds (Boran with zebus and Boran with Sahiwal), while Olkirimatian kept both crossbreeds (Boran with zebus and Boran with Sahiwal) and dual-purpose indigenous cattle.

Animal characteristics and performance data

The study followed the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) to estimate enteric CH_4 emissions. In additions, equations from IPCC (2000) and NRC (2001) were used for the estimation of net energy mobilized due to weight loss and net energy for activity utilizing the daily distance travelled. The Tier 2 method requires local data on various animal characteristics, such as live weight, live weight gain, age, sex, physiological status, milk production, milk quality, work hours, and breed, as well as feed characteristics, including feeding situation and feed digestibility.

In Kapiti, five measurements were taken at the beginning and end of each of the four seasons. However, in Olkirimatian and Shompole, three measurements were taken, aligning with the start and end of the dry season, as well as the end of the subsequent long rainy season.

After the initial farm visit in early 2021, during which the farmers either verbally agreed (Kapiti) or signed consent (Magadi) to participate in the project for the full duration, the researchers conducted repeated farm visits to collect data on live weight, milk yield records, and milk and pasture samples. A representative sub-sample of the herd, 815 cattle in the Kapiti research Ranch, 347 cattle in the Olkirimatian community ranch, and 324 cattle in the Shompole community ranch, was considered in the project. The animals were classified into the following age groups: adult male and female cattle (>3 years), young male and heifers (1–3 years), and calves (<1 year). The animals' age was determined using dentition, following the method described by Torell et al. (2003) when farmers did not know animals' ages. Calves' age was determined by farmer recall. Animals that were missing during subsequent farm visits were replaced with other animals.

Live weight measurement and average daily weight gain/loss

Live weights were measured using calibrated cattle weighing scale (dimensions: 1.2 m × 2 m × 1.3 m; YH-T3 Tscale Electronics MFG, Model KW; Kunshan, China) during each visit. The scale was calibrated with known weights before each weighing session in each household. For Kapiti Ranch, the live weight measurements were taken at the beginning and end of the four distinct seasons in Kenya: hot dry (January to February), long rain (March to May), cold dry (June to October), and short rain (November to December). Due to the drought conditions spanning from 2020 to 2023, the animals in Olkirimatian and Shompole migrated to Tanzania and other parts of Kenya in search of feed and water, showing mobility is better following feed scarcity. Hence, live weight measurements were only possible for the start and end of the cold dry season and the end of long rain.

Average live weight change (LWC) was computed using the difference in live weight for each animal between seasons and divided by the number of days between measurements. If a live weight was missing, the average LWC of the herd was applied. Given that we have different breeds and hence mature weights in the study locations, the study derived mature body weight (MW) for male and female animals from Kenya Livestock Breeds Catalogue (2019) for Kapiti and Government of Kenya (2020) for Olkirimatian and Shompole.

Milk yield and its composition

Daily milk production was recorded by the livestock keepers by measuring the morning and evening milk of each lactating cow using calibrated cans that were provided to the farmers at the beginning of the project. Records were obtained from livestock keepers who were literate, trained in record keeping, and supplied with the necessary record books. The daily milk yield (DMY) was then transferred to data collection sheets and the average daily milk output (DMO) per day per season was calculated from the daily milk yield and daily calf milk consumption (DCMC) using Equation 1.

$$\mathrm{DMO}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) = \mathrm{DMY}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) + \mathrm{DCMC}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) \tag{1}$$

Where; **DMO** is the daily milk output (L/d); **DMY** is the daily milk yield calculated by summing up the total milk for the number of days the livestock keepers recorded the yield and dividing it by the number of days, L/day, and **DCMC** is the daily calf milk consumption (in L/d) of pre-ruminant calves) required for all lactating females accompanied by a young calf using Equation 2.

The DCMC was estimated by following the method of Radostits and Bell (1970).

TABLE 1 Chemical composition of milk (Mean ± SE) in the study area.

Milk composition	Kapiti	Olkirimatian	Shompole
Dry season	N = 37	N = 30	N = 26
Fat (%)	5.7 ± 0.1	5.8 ± 0.3	5.3 ± 0.2
Protein (%)	3.1 ± 0.0	3.3 ± 0.0	3.3 ± 0.0
SNF (%)	8.6 ± 0.0	9.0 ± 0.1	9.2 ± 0.1
Density (g/L)	27.6 ± 0.2	29.3 ± 0.6	30.2 ± 0.5
Lactose (%)	4.7 ± 0.0	5.0 ± 0.1	5.0 ± 0.1
Wet season	N = 40	N = 30	N = 26
Fat (%)	5.4 ± 3.2	6.3 ± 0.1	6.4 ± 0.3
Protein (%)	3.0 ± 0.0	3.4 ± 0.1	3.1 ± 0.0
SNF (%)	8.3 ± 0.1	9.4 ± 0.2	8.6 ± 0.1
Density (g/L)	26.9 ± 0.2	30.4 ± 0.8	27.1 ± 0.4
Lactose (%)	4.6 ± 0.0	5.2 ± 0.1	4.7 ± 0.1

N, number of observations.

$$\mathrm{DCMC}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) = \mathrm{LW}\ (\mathrm{kg}) \times 0.107\left(\frac{\mathrm{L}}{\mathrm{kg}}\right) + 3.39\left(\frac{\mathrm{L}}{\mathrm{kg}}\right) \times \mathrm{LWC}\left(\frac{\mathrm{kg}}{\mathrm{d}}\right) \tag{2}$$

Where; **DCMC** is the daily calf milk consumption; **LW** is the live weight of the calf; **0.107** is the constant representing the amount of milk, the calves need for maintenance for every 1 kg of LW.; **3.39** is the constant representing the amount in L required by the calves to gain one kg of live weight; **LWC** is the average live weight change per day.

Furthermore, milk quality was estimated from morning milk samples from representative lactating cows. The milk samples were collected on random days in a season and the samples were kept in a cooling box and analysed the same day with a portable milk analyzer (Lactoscan S Standard 1040, Bulgaria) for butter fat content (BF%), protein content (%), lactose content (%), and specific gravity. Results are shown in Table 1.

Feed characterization and quality

The researchers collected information about the seasonal feed types directly from farmers or farm staff. A composite sample of the different plant materials consumed by cattle were collected from the three study locations, and pooled per location, and their fresh weights were recorded. The samples were then oven-dried at 50°C until a constant weight was reached (3–5 days), ground using a hammer mill, and passed through a 1 mm sieve. The ground samples were stored in sealed plastic containers at room temperature until analysis. The recommended procedure of AOAC International (2006) (2005) was followed for analyzing dry matter (DM, Method 930.15), total nitrogen (N, AOAC Method 990.03), acid detergent fiber (ADF), and neutral detergent fiber (NDF) (AOAC Method 973.18). The gross energy content of the feeds was determined using a Bomb calorimeter (Par 6300, Par Instruments, (Korir et al., 2022)) using standard protocol. Finally, the seasonal dry matter digestibility (DMD) was estimated from the equation of Oddy et al. (1983), as follows using Equation 3:

$$\mathrm{DMD}\left(\frac{\mathrm{g}}{100\mathrm{g\,DM}}\right) = 83.58 - 0.824 \times \mathrm{ADF}\left(\frac{\mathrm{g}}{100\mathrm{g\,DM}}\right) + 2.626 \times \mathrm{N}\left(\frac{\mathrm{g}}{100\mathrm{g\,DM}}\right) \tag{3}$$

where; **DMD** is dry matter digestibility, % or g/100 g DM; **ADF** is acid detergent fiber, % or g/100 g DM, and **N** is nitrogen content in the feed, % or g/100 g DM.

Subsequently, the DE % was estimated from the seasonal DMD using Equation 4 derived from CSIRO (2007), as IPCC methodology utilizes digestible energy (DE, % of gross energy) for the calculation of net energy requirements,

$$\mathrm{DE}\,\% = \frac{\mathrm{DMD}\,(\%) \times 0.172 - 1.707}{0.81 \times \mathrm{GE}\left(\frac{\mathrm{MJ}}{\mathrm{kg\,DM}}\right)} \times 100 \tag{4}$$

Where; **DE %** is the digestible energy as a percentage of feed gross energy; **DMD** is seasonal dry matter digestibility, %, as estimated in Equation 1, **0.172** and **1.707** are constants used in a formula to convert **DMD** into megajoules (MJ) of metabolizable energy per kilogram of dry matter (DM); **0.81** is a factor that converts metabolizable energy to digestible energy; GE is gross energy of feed (MJ/kg DM).

Locomotion data

The average daily distance traveled was determined using GPS collars. Collars were attached in the morning before releasing the animals for grazing on randomly selected cattle. Due to the limited number of collars and to obtain data from as many animals as possible per season, collars were changed between animals every 3 days (Goopy et al., 2018; Ndung'u et al., 2020). As the animals were confined at night, only data collected between 6:00 a.m in the morning and 7:00 p.m. were considered. Data were obtained from ten cattle during the dry season and eight cattle during the wet season. Enteric CH_4 emission.

Based on the 2019 Refinement to the IPCC (2006), the daily enteric EF was calculated from gross energy intake (GEI) and Ym (the fraction of gross energy intake released in the form of CH_4). The following Tier 2 equation (Equation 5) from IPCC (2019) was used to compute seasonal EF and annual EF:

$$\mathrm{EF_{season}}\left(\frac{\mathrm{kg\,CH4}}{\mathrm{season}}\right) = \left[\frac{\left(\mathrm{GEI}\left(\frac{MJ}{day}\right) \times \frac{\mathrm{Ym}\,(\%)}{100}\right)}{55.65\left(\frac{\mathrm{MJ}}{\mathrm{kg\,CH4}}\right)}\right] * days\ in\ season \tag{5}$$

where $\mathbf{EF_{season}}$ represents the enteric CH_4 emission factor (in kg CH_4/head/season) estimated from seasonal animal characteristics and performance data based on the IPCC (2019) Tier 2 Equation 10.21, **GEI** is the gross energy intake (in MJ/d) calculated using IPCC equations, and **Ym** is the CH_4 conversion factor, the IPCC (2019) default value of 7.0% was used due to the absence of site-specific value. The factor 55.65 (MJ/kg CH_4) is the energy content of CH_4. Equation 6 shows how the annual **EF** for enteric CH_4 emission (kg CH_4/head/year) was estimated.

$$Annual\ \mathrm{EF}\left(\mathrm{kg}\frac{\mathrm{CH4}}{\mathrm{year}}\right) = \left(\frac{\mathrm{EF_{season1}}\left(\frac{\mathrm{kg\,CH4}}{\mathrm{season}}\right) + \mathrm{EF_{season\,2}}\left(\frac{\mathrm{kg\,CH4}}{\mathrm{season}}\right) + \cdots}{\mathrm{Number\ of\ seasons}}\right) \tag{6}$$

The GEI was calculated using Equation 7 derived from IPCC (2019), with the incorporation of the net energy mobilized ($\mathbf{NE_{mob}}$) due to weight loss as per IPCC (2000) and the calculation of net energy for travel (NE_t) instead of net energy for activity (NE_a) using the daily distance traveled as per NRC (2001).

$$\mathrm{GEI\,(MJ/d)} = \left[\frac{\left(\frac{\mathrm{NE_m}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_t}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_l}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_p}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_{mob}}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right)}{\mathrm{REM}}\right) + \left(\frac{\mathrm{NE_g}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right)}{\mathrm{REG}}\right)}{\mathrm{DE\,(\%)/100}}\right] \tag{7}$$

where **GEI** is gross energy intake, MJ/d; $\mathbf{NE_m}$ is net energy required by the animal for maintenance MJ/d; $\mathbf{NE_t}$ is net for travel, MJ/d; $\mathbf{NE_l}$ is net energy for lactation, MJ/d; $\mathbf{NE_p}$ is net energy for pregnancy, MJ/d; $\mathbf{NE_{mob}}$ is net energy due to weight loss (mobilized), MJ/d; **REM** is the ratio of net energy available in a diet for maintenance to digestible energy; $\mathbf{NE_g}$ is net energy needed for growth, MJ/day; **REG** is the ratio of net energy available for growth in a diet to digestible energy consumed; **DE** is the energy digestibility of feed in each season expressed as a fraction of gross energy (digestible energy/gross energy). The net energy of work was not included in the equation because animals were not used for work.

The NE_m, NE_l, NE_p NE_g, REM, and REG were calculated as per the respective equations in the IPCC (2019) guidelines as shown in the Supplementary Material.

The NE_t was estimated based on Equation 8 derived from NRC (2001) as,

$$\mathrm{NE_t}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) = \left(\mathrm{Dist\ (km)} \times 0.0019\left(\frac{MJ/kg}{km}\right) \times \mathrm{MLW\,(kg)}\right) + \left(0.005\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right) \times \mathrm{MLW\ (kg)}\right) \tag{8}$$

Where, $\mathbf{NE_t}$ is net energy for travel, MJ/d; **Dist.** (in km) is the average daily distance traveled per season, (data obtained from GPS collar); **0.0019** is the energy (MJ) required per kg LW per kg of walking; MLW is the mean seasonal LW in kg; and **0.005** is the energy (MJ) required per kg LW during grazing.

If live weight loss was observed per season, the net energy mobilized (NE_{mob}) was calculated for lactating and other cattle using Equation 9.

The NE_{mob} for lactating cows was calculated as,

$$NE_{mob}\left(\frac{MJ}{d}\right) = 19.7\left(\frac{MJ/kg}{d}\right) \times LWC\ (kg) \tag{9}$$

where $\mathbf{NE_{mob}}$ is the net energy due to weight loss (mobilized), MJ/day; 19.7 is the amount of energy (in MJ) mobilized per kg of weight loss; and **LWC** is average daily weight loss as calculated in Equation 10. Weight loss is taken, such that the estimated NE_{mob} is a negative number.

Seasonal average LWC (kg/day) was calculated per animal per season using Equation 10,

$$LWC\left(\frac{kg}{D}\right) = \frac{LW_{\text{End of season}}\ (kg) - LW_{\text{Start of season}}\ (kg)}{\text{Number of days between measurements}} \tag{10}$$

Where, **LWC** is the average daily live weight change between measurements, kg/day; and **LW** is the measured live weight of the individual animal, in kg.

For other cattle, the amount of energy mobilized through weight loss (NE_{mob}) was calculated by: (1) inserting the LWC (kg/d) as a positive number into Equation 12 to calculate NE_g, and (2) calculating NE_{mob} as negative 0.8 times this NE_g value (IPCC, 2000).

$$NE_{mob}\left(\frac{MJ}{d}\right) = NE_g\left(\frac{MJ}{d}\right) \times (-0.8) \tag{11}$$

Where $\mathbf{NE_{mob}}$ is the net energy mobilized through weight loss (mobilized), MJ/d. It is a negative number; $\mathbf{NE_g}$ is net energy for growth, MJ/d, calculated by inserting LWC as positive in Equation 11; and −0.8 is the fraction of NEg mobilized through weight loss (IPCC, 2000).

The NE_g was calculated following Equation 12.

$$NE_g\left(\frac{MJ}{d}\right) = 22.02 \times \left(\frac{MLW\ (kg)}{C \times MW\ (kg))}\right)^{0.75} \times LWC^{1.097}\ (kg) \tag{12}$$

Where, $\mathbf{NE_g}$ is the net energy needed for growth, MJ/d; **MLW** is the average LW in the season, kg; **C** is a coefficient with a value of 0.8 for females, 1.0 for castrates, and 1.2 for bulls (NRC, 1996); **MW** is the mature body weight of an adult animal individually, mature females, mature males, and steers) in moderate body condition, kg; LWC is the average daily live weight change in the season, kg/d.

Data analysis

Quantitative data analysis used descriptive statistics and one-way analysis of variance (ANOVA). The one-way ANOVA was employed to examine the variation in mean annual live weights, live weight change, and emission factors (EF) across the three locations. A *post hoc* test (Tukey test) was conducted to compare means. Mean annual values for LW, LWC, and EF were calculated by averaging the data from four seasons in Kapiti and two seasons each in Olkirimatian and Shompole. The analyses were carried out using R software and the Microsoft Excel. In all analyses, *p*-values less than 0.05 were considered statistically significant.

Results

Herd characteristics

The cattle were classified into five categories based on age and sex (Table 2). The composition of the herds varied across the three locations, with Kapiti Ranch having the largest female cattle population.

Animal liveweights for all animal classes were substantially larger at Kapiti compared to Olkirimatian and Shompole (Table 2).

In Kapiti, adult females, growing males and females and calves had a 5%–78% higher LW than the (IPCC 2019) Tier 1 value, while adult males had 18% lower LW. All cattle categories except calves had a 13%–29% and 9.8%–27% lower LW than the IPCC Tier 1 values in Olkirimatian and Shompole, respectively (Table 2).

Kapiti had a higher milk yield than Olkirimatian, with a 129% difference. It had a 62% higher milk yield than the IPCC Tier 1, while Olkirimatian and Shompole had a 29% and 46% lower milk yield, respectively.

Across all animal categories, there were no statistical differences concerning annual mean LWC among the three locations, except for adult males, where Olkirimatian exhibited higher annual mean LWC compared to Kapiti and Shompole (Table 3).

Feed quality

Grazing was the principal feeding system throughout the year in the three rangeland systems and supplementation was not a common practice. The quality of cattle feed, as indicated by various parameters, varied among the three locations. Among the three locations, Shompole generally exhibited the highest DE values (Table 4).

Enteric CH_4 production

The CH_4 EF for different categories of cattle across the three study locations of Kapiti, Olkirimatian, and Shompole showed

TABLE 2 Herd structure, mean live weight, (kg, mean ± SE), and average daily milk yield (l, mean ± SE) for the three study locations in Kenya.

Cattle category	Kapiti		Olkirimatian		Shompole		IPCC (2019) Tier 1
	Mean ± SE	N	Mean ± SE	N	Mean ± SE	N	Mean LW
Adult females	374[a] ± 3	234	251[b] ± 5	87	250[b] ± 4	93	356
Adult males	441[a] ± 9	54	249[c] ± 9	71	385[b] ± 17	21	540
Young females	238[a] ± 3	207	173[b] ± 8	45	195[b] ± 5	75	204
Young males	252[a] ± 4	156	177[b] ± 6	67	184[b] ± 6	54	204
Calves	146[a] ± 3	164	90[b] ± 4	77	96[b] ± 3	81	82
Milk yield	3.9[a] ± 0.1	158	1.7[b] ± 0.1	79	3.5[a] ± 0.0	22	2.4

N = number of observations; Adult females (≥3 years); Adult males (≥3 years); young females (1–3 years); young males (1–3 years); Calves (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$.
NB: IPCC Tier 1 values are derived from the pasture/range systems mentioned in the IPCC (2019) Guidelines Table 10A.2 (New).

TABLE 3 Mean live weight change (g/d, mean ± SE) for the three study locations in Kenya.

Cattle category	Kapiti		Olkirimatian		Shompole		IPCC (2019) Tier 1
	Mean ± SE	N	Mean ± SE	N	Mean ± SE	N	Mean
Adult females	44[a] ± 11	234	70[a] ± 15	87	50[a] ± 12	93	0
Adult males	115[b] ± 24	54	283[a] ± 27	71	125[b] ± 50	21	0
Young females	220[a] ± 9	207	302[a] ± 25	45	218[a] ± 15	75	240
Young males	237[a] ± 14	156	283[a] ± 25	67	244[a] ± 20	54	240
Calves	240[a] ± 13	164	254[a] ± 14	77	288[a] ± 11	81	330

N, number of observations; Adult females (≥3 years); Adult males (≥3 years); young females (1–3 years); young males (1–3 years); Calves (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$.
NB: IPCC Tier 1 values are derived from the pasture/range systems mentioned in the IPCC (2019) Guidelines Table 10A.2 (New).

variations. In general, Kapiti tended to have higher EF compared to Olkirimatian and Shompole for all cattle categories. For instance, the overall EF in Kapiti was 25% and 55% higher than Olkirimatian and Shompole, respectively. This trend was also evident for adult males, heifers, young males, and calves, where Kapiti consistently showed higher EF compared to the other locations.

For Kapiti, the Tier 2 EFs for adult females were 22% higher than the IPCC Tier 1, while for Olkirimatian and Shompole, they were 11% and 27% lower EF than IPCC Tier 1, respectively. Heifers in Kapiti and Olkirimatian had 20% and 7% higher Tier 2 EFs than IPCC Tier 1, while in Shompole, Tier 2 EFs were 11% smaller than Tier 1 EFs.

Discussion

Notable differences were observed in the cattle within the three locations. Specifically, the cattle in Kapiti had greater LW and higher milk production compared to those in Olkirimatian and Shompole. These differences in LW and milk production are attributed to factors such as breed.

The Tier 2 enteric CH_4 EF of cattle in Kapiti consistently ranked the highest across all categories when compared to the other two locations. This observation aligns with the understanding that LW plays a significant role in determining NE_m (Ndung'u et al., 2020). In general, the site with the highest LW tended to have the highest EFs, which generally aligned with the hypothesis.

Differences in EF were not consistent for all study sites: Shompole had a higher mean LW than Olkirimatian across all animal classes, but it displayed lower EFs for all animal classes except adult males. This discrepancy can be attributed to the statistically lower LWC in Shompole than in Olkirimatian, except calves, which resulted in a higher net energy mobilized or lower net energy for weight gain. The higher EF of calves in Olkirimatian despite the lower LWC can be attributed to a higher proportion of pre-ruminant calves (<3 months) in Shompole (55% vs. 25%). Since the rumen of pre-ruminant calves is not fully developed, the emission from these animals was assumed to be negligible (Marquardt et al., 2020). The calves in Shompole had higher EF because higher proportion of pre-ruminant calves with lower EFs were excluded from the calculations.

TABLE 4 Quality of cattle feed in the study locations in Kenya.

Feed quality	Kapiti	Olkirimatian	Shompole
Dry season			
DM, %	92.8 ± 0.2	92.2 ± 0.3	92.5 ± 0.3
NDF, %	68.5 ± 1.0	NA	NA
ADF, %	39.3 ± 0.5	36.1 ± 2.2	32.5 ± 2.0
N, %	0.8 ± 0.1	1.3 ± 0.2	1.8 ± 0.2
GE, MJ/kg DM	16.9 ± 0.3	17.3 ± 0.3	17.0 ± 0.2
DMD, %	53.2 ± 0.5	57.3 ± 2.4	61.6 ± 2.2
DE, %	54.5 ± 0.9	58.8 ± 3.6	64.6 ± 2.9
Wet season			
DM, %	93.7 ± 0.2	93.1 ± 0.3	93.4 ± 0.3
NDF, %	62.1 ± 2.4	NA	NA
ADF, %	37.2 ± 1.4	34.2 ± 2.2	30.8 ± 2.0
N, %	1.0 ± 0.1	1.6 ± 0.2	2.3 ± 0.2
GE, KJ/kg DM	17.3 ± 0.1	17.7 ± 0.3	17.4 ± 0.2
DMD, %	55.7 ± 1.5	60.0 ± 2.4	64.5 ± 2.2
DE, %	56.0 ± 1.8	60.4 ± 3.6	66.4 ± 2.9

DM, dry matter; NDF, Neutral detergent fiber; ADF, Acid detergent fiber; N, nitrogen; GE, gross energy; DMD, Dry matter digestibility and DE, feed digestibility expressed as percent of gross energy. NA, No assessment.

Additionally, 10% higher DE% in Shompole compared to Olkirimatian are likely to contribute to the lower EFs in Shompole. The DE variation showed the analysis result of the composite pasture sample. The variation in DE of the pasture across the three locations is generally consistent with the findings of Lee et al. (2017) who showed the variability in the nutritional quality of forage grasses in different locations.

Normally, it is assumed that enteric CH_4 emissions in adult females, including both lactating and dry cows, increase with rising levels of total milk production of the cows (Goopy et al., 2018). Although the mean daily milk output (DMO) of lactating cows was higher in Shompole compared to Olkirimatian (Table 2), the EF of adult females in Shompole was lower, mainly because of the smaller proportion of lactating animals in Shompole than in Olkirimatian (24% vs. 91%, Table 5). As a result, the annual mean NE_l in Shompole was statistically lower (Supplementary Table S5).

The observed differences in enteric CH_4 EFs among Kapiti, Olkirimatian, and Shompole can be largely attributed to variations in management practices across these locations. Kapiti Research Station operates as an extensive ranching system with controlled grazing, improved pasture management, and the use of crossbred cattle (Boran × Holstein), which tend to have higher productivity and LW. This more regulated system allows for better nutritional management and consistent animal performance, contributing to higher emission factors per animal but potentially lower emission intensity per unit of product. In contrast, Olkirimatian and Shompole represent community-managed pastoral systems characterized by herd mobility, communal grazing, and a predominance of indigenous or crossbred zebu cattle. Lower LW, reduced LW gain, and variable feed quality in these settings resulted in lower annual CH_4 emissions per animal compared to the ranching system at Kapiti.

Additionally, the differences in herd structure, such as a higher proportion of young and non-lactating animals in the pastoral systems, further influenced the emission profiles. Communal management and reliance on natural pastures in pastoral systems typically lead to lower productivity, which, while reducing absolute emissions per animal, may increase emission intensity per unit of product (e.g., milk or meat). These findings highlight the importance of tailoring mitigation strategies and national inventories to account for the diversity of management practices and production environments in Kenya's rangelands.

It was not possible to estimate the statistical differences between the estimated Tier 2 EFs and the IPCC Tier 1 values, because there is only one Tier 1 value. However, numerical differences were observed between Tier 2 and Tier 1 EFs, although the difference was not consistent in the three

TABLE 5 Tier 2 Emission factors (mean ± SE, kg CH_4/head/year) for different categories of cattle in the three study locations].

Cattle category	Kapiti		Olkirimatian		Shompole		IPCC (2019) Tier 1
	Mean ± SE	N	Mean ± SE	N	Mean ± SE	N	Mean
Adult females	$90.4^{a} \pm 1.4$	234	$66.3^{b} \pm 1.5$	87	$54.5^{c} \pm 1.2$	93	74
Lactating	$101.0^{a} \pm 1.4$	158	$66.5^{b} \pm 1.5$	79	$63.0^{b} \pm 3.1$	22	
Non-lactating	$68.5^{a} \pm 1.4$	76	$53.4^{b} \pm 5.3$	8	$51.1^{b} \pm 1.1$	71	
Adult males	$82.9^{a} \pm 1.6$	54	$70.8^{b} \pm 2.7$	71	$75.4^{ab} \pm 3.0$	21	79
Young females	$54.9^{a} \pm 0.8$	207	$48.5^{ab} \pm 2.2$	45	$41.1^{b} \pm 1.1$	75	46
Young males	$56.3^{a} \pm 0.9$	156	$43.0^{b} \pm 1.5$	67	$36.4^{b} \pm 1.5$	54	46
Calves	$39.5^{a} \pm 0.6$	164	$25.5^{b} \pm 1.0$	77	$22.0^{b} \pm 0.5$	81	31
Overall	$64.5^{a} \pm 0.9$	815	$51.7^{b} \pm 1.2$	347	$41.8^{c} \pm 1.0$	324	

N, number; Adult females (≥3 years); Adult males (≥3 years); young females (1–3 years); young males (1–3 years); Calves (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$.

locations. The difference can be attributed to several parameters. One parameter is the variations in mean LW, which was 18% lower in adult males and 5%–78% higher for other categories of cattle in Kapiti. In Olkirimatian, Tier 2 mean LW was 10% higher in calves and 13%–54% lower for other categories of cattle. In Shompole, it was 17% higher in calves and 4%–29% lower for other categories of cattle (Table 2). Moreover, methodological differences in the calculation of Tier 2 EFs in the present study and Tier 1 estimate contributed to the difference. For instance, IPCC Tier 1 did not consider the NE_{mob} due to weight loss. In contrast, this study estimated the NE_{mob} in the case of weight loss for all categories, following equations adopted from IPCC (2000). Furthermore, according to IPCC (2019) Tier 1, adult animals are typically assumed to have no net weight gain over an entire year, assuming that reduced intakes and emissions associated with weight loss are balanced by increased intakes and emissions during periods of weight gain. However, in the present study, adult animals were observed to show average annual gains although some were observed to lose weight. Hence net energy for growth was calculated for adult animals.

The main difference between Tier 1 and Tier 2 lies in the assumptions made for activity data. The results indicate that using a single default value for the whole of Africa does not adequately capture the diverse regional conditions. Moreover, even within similar systems and regions, variations exist that could be better explained by accounting for breed differences. Therefore, revising IPCC default values to include system-specific estimates for different regions and cattle breeds could help countries without Tier 2 emission factors enhance the accuracy.

The Tier 1 approach applies a fixed DE value for pasture, but our findings show significant variation in observed DE across sites. Understanding whether these differences are linked to agroecological zones, difference in soil composition and if they can be predicted is crucial. Pasture management improvements can enhance pasture digestibility and composition when pasture production and quality is poor. This would lead to higher weight gains, lower feed intake per unit of growth, and ultimately, reduced EFs. Supplementation could be explored during periods of low forage availability to avoid body weight losses, as our findings indicated that some animals experienced body weight loss, highlighting the potential of targeted supplementation strategies in mitigating seasonal nutritional gaps. By improving energy intake during critical periods, supplementation could help stabilize weight gain and reduce the variability in EFs.

A key limitation of this study is the unequal number of measurement periods across the three locations: five at Kapiti and only three at Olkirimatian and Shompole. This discrepancy resulted primarily from the high mobility of pastoral herds in Olkirimatian and Shompole, especially during drought conditions, which made repeated sampling logistically challenging. Consequently, the data from these two sites may not fully capture the extent of seasonal variability in animal performance and CH_4 emissions that could occur under different climatic conditions. Despite this limitation, the three study sites were purposefully selected to represent the diversity of rangeland cattle systems in southern Kenya-Kapiti as an extensive ranching system and Olkirimatian and Shompole as community-managed pastoral systems. While the findings provide valuable system-specific EFs, caution should be exercised in generalizing these results to all rangeland systems in Kenya or similar environments. Future research with more frequent and evenly distributed measurements across all sites and seasons would further strengthen the representativeness and applicability of the EFs generated in this study.

Conclusion

This study provides critical insights into the variability within comparable rangeland systems and its implications for national emission factors (EFs). Our findings demonstrate that using a single default EF for large regions, such as Africa, does not accurately reflect local conditions. Even within geographically similar areas, we observed significant differences in herd composition, live weight (LW), weight gains, milk yield, and digestible energy (DE) of pasture, all of which influence CH_4 emissions.

A key finding is the substantial variation in LW compared to Tier 1 assumptions, as well as significant differences in observed DE across sites, despite the Tier 1 approach assuming a fixed DE. Additionally, we observed body weight loss in some cattle, particularly during periods of low forage availability, emphasizing the potential role of strategic supplementation to maintain weight gain and stabilize emissions. It is important to recognize that in East Africa, pastoralist land use closely mirrors the ecological functions of grazing wildlife, and greenhouse gas emissions from livestock in pastoral systems can be comparable to those from wild herbivores in similar ecosystems. This challenges conventional approaches that attribute all emissions from livestock to pastoral systems as anthropogenic, without accounting for the natural baseline of emissions that would occur from wildlife. Incorporating this perspective into national inventories could lead to more nuanced and equitable climate policies, particularly in wildlife-rich regions such as Kenya and the broader East African rangelands.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal studies were approved by International Livestock Research Institute. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

EG: Writing – original draft, Methodology, Formal Analysis; LK: Data collection; JK: Data collection, Resource mobilization; AS: Data cleaning; SL: Writing – review and editing, Methodology; SM: Writing – review and editing, Conceptualization, Methodology; LM: Writing – review and editing, Conceptualization, Methodology, Fund acquisition; PN: Writing – review and editing, Methodology; CA: Writing – review and editing, Conceptualization, Methodology, Fund acquisition. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The ESSA project (Earth observation and environmental sensing for climate-smart sustainable agropastoralism ecosystem transformation in East Africa) was funded by the European Union through the EU-DeSIRA programme. It also received financial support from the CGIAR Research Initiatives Livestock and Climate and Mitigate+: Low-Emission Food Systems, which are supported by contributors to the CGIAR Trust Fund. Additionally, the work was funded by the International Fund for Agricultural Development (IFAD) through the research projects “Greening Livestock: Incentive-Based Interventions for Reducing the Climate Impact of Livestock in East Africa” (Grant No. 2000000994) and “Programme of Climate Smart Livestock” (PCSL, Programme No. 2017.0119.2). It was also funded by the New Zealand Government to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases. Additional support for this research was provided through CGIAR Science Program on Sustainable Animal and Aquatic Foods, Climate Action, and Multifunctional Landscapes and supported by contributors to the CGIAR Trust Fund. CGIAR is a global research partnership for a food-secure future dedicated to transforming food, land, and water systems in a climate crisis.

Acknowledgments

The authors would like to thank the colleagues of the Mazingira Centre and Kapiti Research Station & Wildlife Conservancy, particularly Nelson Kipchirchir, Elly Kibira, and Nehemiah Kimengich, for their support during field and lab work. We would also like to thank Jane Poole for the guidance on data analysis.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. While preparing the manuscript AI was utilized to check and improve the language.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2025.14566/full#supplementary-material

References

AOAC International (2006). *Official methods of analysis*. Arlington, VA, USA: AOAC International.

Carbonell, V., Merbold, L., Díaz-Pinés, E., Dowling, T. P., and Butterbach-Bahl, K. (2021). Nitrogen cycling in pastoral livestock systems in sub-saharan Africa: Knowns and unknowns. *Ecol. Appl.* 31 (6), e02368. doi:10.1002/eap.2368

CSIRO (2007). *Nutrient requirements of domesticated ruminants*. Collingwood, VIC, Australia: CSIRO Publishing.

Gerber, P., Hristov, A., Henderson, B., Makkar, H., Oh, J., Lee, C., et al. (2013). Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: A review. *animal* 7 (s2), 220–234. doi:10.1017/s1751731113000876

GIZ (2022). "Pastoralism and resilience of Food production in the face of climate change," in *Technical background paper*. Editors Saverio, K., Christine, L., Friederike, M., Wiebke, F., and Tobias, F. (Bonn and Eschborn, Germany).

Goopy, J. P., Ndung'u, P. W., Onyango, A., Kirui, P., and Butterbach-Bahl, K. (2021). Calculation of new enteric methane emission factors for small ruminants in western Kenya highlights the heterogeneity of smallholder production systems. *Animal Prod. Sci.* 61 (6), 602–612. doi:10.1071/an19631

Goopy, J. P., Onyango, A. A., Dickhoefer, U., and 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. doi:10.1016/j.agsy.2017.12.004

Government of Kenya (2020). Inventory of GHG emissions from dairy cattle in Kenya 1995-2017. Available online at: http://www.kilimo.go.ke/wp-content/uploads/2020/07/Kenya-Dairy-Cattle-GHG-inventory-Report_06_07_2020.pdf.

IPCC (2000). "Good practice guidance and uncertainty management in national greenhouse gas inventories. Chapter 4: agriculture," in *Methodology report*. Editors Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., and Emmanuel, S.

IPCC (2006). "Emissions from Livestock and Manure Management," in *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*. Editors Dong, H., Mangino, J., McAllister, T. A., Hatfield, J. L., Johnson, D. E., Lassey, K. R., et al. (Geneva, Switzerland: IPCC), Chapter 10.

IPCC (2019). "Emissions from livestock and manure managemen," in *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume 4: agriculture, forestry and other land use*. Editors Buendia, E. C., Tanabe, K., Kranjc, A., Jamsranjav, B., Fukuda, M., and Ngarize, S. (Geneva, Switzerland: IPCC). *Chapter 10.*

IPCC (2021). "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Editors Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berge, S., et al. (Geneva, Switzerland: IPCC). Cambridge, United Kingdom: Cambridge University Press. 3–32.

Kenya Livestock Breeds Catalogue (2019). Ministry of agriculture, livestock, fisheries and cooperatives state department of livestock, AU-IBAR

Korir, D., Marquardt, S., Eckard, R., Sanchez, A., Dickhoefer, U., Merbold, L., et al. (2022). Weight gain and enteric methane production of cattle fed on tropical grasses. *Animal Prod. Sci.* 63 (2), 120–132. doi:10.1071/an21327

Kosgey, I., Rowlands, G., van Arendonk, J. A., and Baker, R. (2008). Small ruminant production in smallholder and pastoral/extensive farming systems in Kenya. *Small Ruminant Res.* 77 (1), 11–24. doi:10.1016/j.smallrumres.2008.02.005

Lee, M. A., Davis, A. P., Chagunda, M. G., and Manning, P. (2017). Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences* 14 (6), 1403–1417. doi:10.5194/bg-14-1403-2017

Lutta, I. A., Wasonga, V. O., Karanja, R., Saalu, F., and Njiru, J. (2021). "Costs and benefits of sustainable rangeland management practices in Northern Kenya," in *Report for the economics of land degradation initiative in the framework of the "reversing land degradation in Africa through scaling-up evergreen agriculture*. project.

Marquardt, S., Ndung'u, P., Onyango, A. A., and Merbold, L. (2020). "Protocol for a Tier 2 approach to generate region-specific enteric methane emission factors (EF) for cattle kept in smallholder systems," in *ILRI manual*.

Mwaura, F., Ngigi, M., and Obare, G. (2019). Determinants of households' agricultural and energy associated greenhouse Gases emissions among smallholders in western Kenya. *J. Sustain. Dev.* 12 (4), 177. doi:10.5539/jsd.v12n4p177

Ndiritu, S. W. (2021). Drought responses and adaptation strategies to climate change by pastoralists in the semi-arid area, Laikipia County, Kenya. *Mitig. Adapt. strategies Glob. Change* 26 (10), 10–18. doi:10.1007/s11027-021-09949-2

Ndung'u, P. W., Bebe, B., Ondiek, J., Butterbach-Bahl, K., Merbold, L., and Goopy, J. (2020). Corrigendum to: improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: Livestock systems of nandi county, Kenya. *Animal Prod. Sci.* 60 (13), 1668. doi:10.1071/an17809_co

Ndung'u, P. W., Takahashi, T., Du Toit, C. J. L., Robertson-Dean, M., Butterbach-Bahl, K., McAuliffe, G., et al. (2022). Farm-level emission intensities of smallholder cattle (*Bos indicus*; B. indicus–B. taurus crosses) production systems in highlands and semi-arid regions. *Animal* 16 (1), 100445. doi:10.1016/j.animal.2021.100445

Ng'ang'a, S. K., Bulte, E. H., Giller, K. E., Ndiwa, N. N., Kifugo, S. C., McIntire, J. M., et al. (2016). Livestock wealth and social capital as insurance against climate risk: a case study of samburu county in Kenya. *Agric. Syst.* 146, 44–54. doi:10.1016/j.agsy.2016.04.004

Ngetich, W., K Gitau, G., O Abuom, T., and O Aboge, G. (2023). Description of cattle production systems in different agro-ecological zones of Narok County, Kenya. *East Afr. J. Sci. Technol. Innovation* 4 (4). doi:10.37425/eajsti.v4i4.765

Njarui, D., Gichangi, E., Gatheru, M., Nyambati, E., Ondiko, C., Njunie, M., et al. (2016). A comparative analysis of livestock farming in smallholder mixed crop-livestock systems in Kenya: 1. Livestock inventory and management. *Livest. Res. Rural Dev.* 28 (4). Available online at: http://www.lrrd.org/lrrd28/24/njar28066.html.

NRC (1996). *Nutrient requirements of beef cattle, national research council*. Washington, DC: National Academy Press.

NRC (2001). *Nutrient requirements of dairy cattle, national research council*. Washington, USA: National Academy Press.

Oba, G. (2011). "Mobility and the sustainability of the pastoral production system in Africa: Perspectives of contrasting paradigms," in *Future of pastoral peoples in Africa organized by" pastoralism" in the future agriculture consortium at ILRI in addis ababa, Ethiopia from*, 21–23.

Oddy, V., Robards, G., and Low, S. (1983). "Prediction of in vivo dry matter digestibility from the fibre and nitrogen content of a feed," in *Feed information and animal production*. Editors G. E. Robards and R. G. Packham (Farnham Royal, United Kingdom: Commonwealth Agricultural Bureaux). 395–398.

Ontiri, E. M., and Robinson, L. W. (2018). "Community-based rangeland management in Shompole and Olkiramatian group ranches, Kenya: taking successes in land restoration to scale project," in *ILRI project report* (Nairobi, Kenya: ILRI).

Ortiz-Gonzalo, D., Vaast, P., Oelofse, M., de Neergaard, A., Albrecht, A., and Rosenstock, T. S. (2017). Farm-scale greenhouse gas balances, hotspots and uncertainties in smallholder crop-livestock systems in Central Kenya. *Agric. Ecosyst. and Environ.* 248, 58–70. doi:10.1016/j.agee.2017.06.002

Radostits, O., and Bell, J. (1970). Nutrition of the pre-ruminant dairy calf with special reference to the digestion and absorption of nutrients: a review. *Can. J. Animal Sci.* 50 (3), 405–452. doi:10.4141/cjas70-063

Thornton, P., Enahoro, D., Njiru, N., van Wijk, M., Ashley, L., Cramer, L., et al. (2019). "Program for climate-smart livestock systems," in *Country stocktake: Kenya, ILRI report* (Nairobi, Kenya: ILRI).

Torell, R., Bruce, B., Kvasnicka, B., and Conley, K. (2003). "Methods of determining age of cattle," in *Cattle producer's library: CL712* (Reno, NV: University of Nevada). Available online at: http://www.unce.unr.edu/publications/files/ag/other/cl712.pdf (Accessed August 2, 2023)

WISP (2008). Sustainable Pastoralism – moving forward with appropriate policies.

Yurco, K. (2017). Herders and herdsmen: the remaking of pastoral livelihoods in Laikipia, Kenya. *Pastoralism* 7, 15–11. doi:10.1186/s13570-017-0086-0