CSIRO PUBLISHING

Animal Production Science
https://doi.org/10.1071/AN19631

Calculation of new enteric methane emission factors for small ruminants in western Kenya highlights the heterogeneity of smallholder production systems

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Abstract

Context. African livestock play a critical role in food security and the wider economy, while accounting for >70% of African agricultural greenhouse gas emissions. Accurate estimates of greenhouse gas emissions from livestock are required for inventory purposes and to assess the efficacy of mitigation measures. While there is an increasing number of studies assessing methane (CH_4) emissions of cattle, little attention has been paid to small ruminants (SR).

Aims. Enteric CH_4 emissions were assessed from 1345 SR in three counties of western Kenya to develop more accurate emission factors (EF) for enteric CH_4 from sheep and goats.

Methods. Using on-farm animal activity data, feed samples were also analysed to produce estimates of feed digestibility by season and region. The combined data were also used to estimate daily CH_4 production by season, location and class of animal to produce new EF for annual enteric CH_4 production of SR.

Key results. Mean dry-matter digestibility of the feed basket was in the range of 58–64%, depending on region and season (~10% greater than Tier I estimates). EF were similar for sheep (4.4 vs 5 kg CH_4/year), but lower for goats (3.7 vs 5 kg CH_4/year) than those given for SR in developing countries in Intergovernmental Panel on Climate Change (Tier I) estimates.

Conclusions. Published estimates of EF for SR range widely across Africa. In smallholder systems in western Kenya, SR appear to be managed differently from cattle, and EF appear to be driven by different management considerations.

Implications. The findings highlighted the heterogenous nature of SR enteric emissions in East Africa, but also suggested that emissions from SR are quantitatively less important than other estimates suggest compared with cattle.

Keywords: agricultural systems, climate, goats, methane, sheep.

Received 1 November 2019, accepted 5 December 2020, published online 25 February 2021

Introduction

Livestock, whether in pastoralist or mixed cropping–livestock systems, are a cornerstone of agriculture in Sub-Saharan Africa and ruminant livestock, in particular, underpin the livelihoods of African subsistence and emerging farmers (McPeak and Little 2006; Herrero *et al*. 2010). However, paradoxically, ruminants both contribute to and are affected by the increasing impact of climate change as a consequence of anthropogenic greenhouse gas (GHG) emissions. Given the importance of livestock, and specifically of ruminants, as a source of global GHG emissions, several authors have emphasised the need for more accurate estimates of GHG from livestock in developing countries, so as to improve the understanding of sinks and sources of global GHG emissions and to develop strategies to mitigate emissions from the agricultural sector. Whereas emissions from the livestock sector are rather well described in the West, little is known for Sub-Saharan Africa (SSA), although recently there has been an upsurge of interest in improving inventories for SSA.

Most attention has been paid to cattle, whose greater numbers and larger body size make them the most economically important species of domestic ruminant in SSA (Jahnke *et al*. 1988), constituting 70–85% of total ruminant biomass (Herrero *et al*. 2008). Notwithstanding, it has been estimated that livestock contribute 70% or more of African agricultural GHG emissions (dominated by methane (CH_4) from enteric fermentation; Tubiello *et al*. 2014) and small ruminants (SR) will undoubtedly be responsible for a significant part of this (Herrero *et al*. 2008).

A substantial impediment to improving our understanding of the contribution of SR to GHGs in SSA is the continued use of Intergovernmental Panel on Climate Change (IPCC) (Tier I) default emission factors (EF) to estimate enteric CH_4 emissions. The Tier I EF, which employs a universal factor for all animals of one species (in Africa), fails to properly account for differences in production systems across various climatic zones, as demonstrated by the modelling approach of Herrero *et al*. (2008). To place the importance of spatially explicit data in context, of the two known African studies that have produced revised EF for SR, the South African study (Du Toit *et al*. 2013) found that Tier I estimates were 20–40% lower than the calculated EF for SR, while Ndao *et al*. (2019) found that Tier I overestimated the EF of West African sheep and goats by 50–65%. Clearly, there is a need to develop, at least, region-specific estimates for SR EF. A further consideration is that both seasonal fluxes in the availability and quality of feed in combination with husbandry practices are likely to profoundly affect the animals' ability to meet their nutritional requirements and this, in turn, affects enteric CH_4 production, and hence EF, in a way not properly accounted for by IPCC methodology (Goopy *et al*. 2018, 2020; Ndung'u *et al*. 2019).

In the present study, field assessments were conducted in three counties in western Kenya and detailed animal measurements were used to produce estimates of energy expenditure and feed intake and, thereby, estimates of individual CH_4 production rate (daily methane production: DMP: CH_4 g/d), and ultimately EF, were developed.

Materials and methods

Study areas

Detailed farm surveys were conducted in three areas of western Kenya (see Fig. 1), two of which (Nyando and Nandi) have been published elsewhere, and were concerned with enteric emissions from cattle. These are briefly outlined below.

Study site I was a 10 × 10 km^2 block in the Nyando Basin of western Kenya (0°13′30″S–0°24′0″S, 34°54′0″E–35°4′30″E), with the study area being further divided into three distinct agro-ecological zones (AEZ), plains, mid-slopes and uplands. Details of both the site and the sampling protocol have been published in Goopy *et al*. (2018). Study site II was

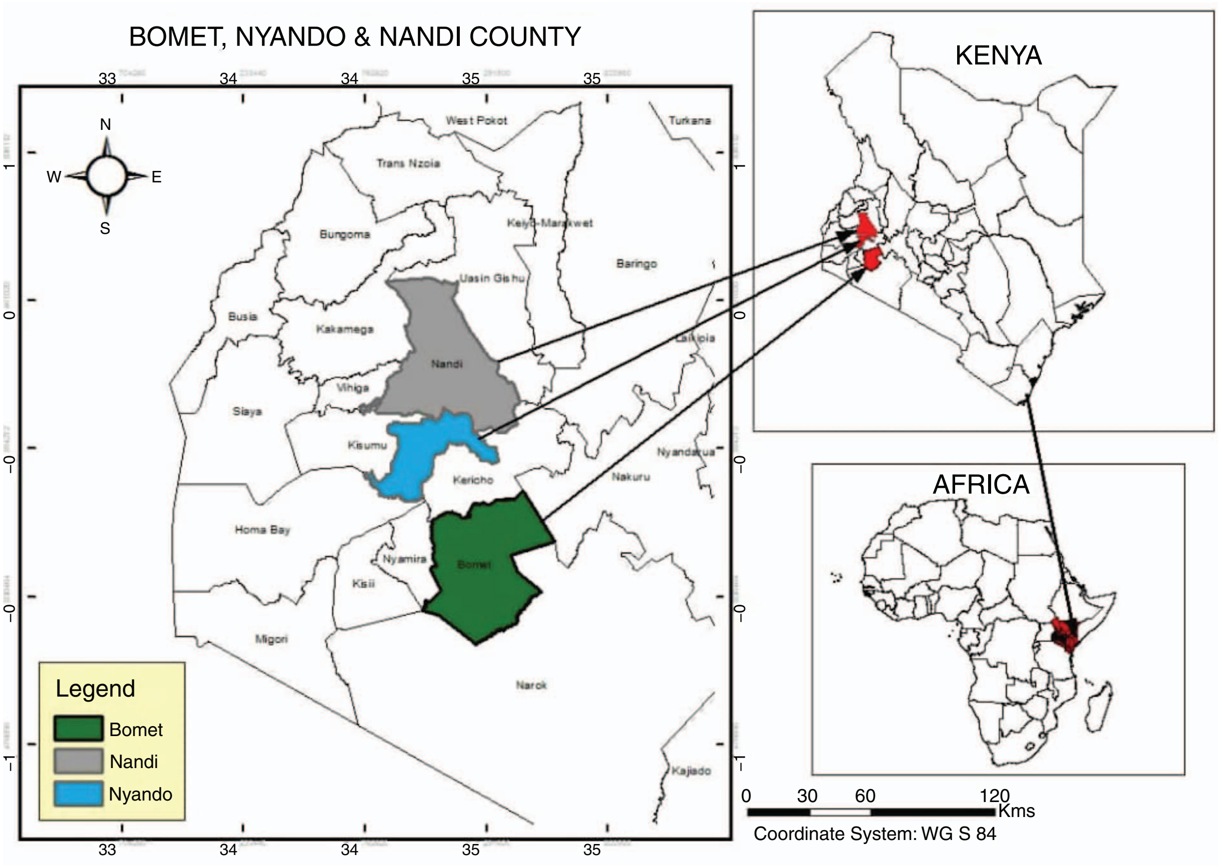

Fig. 1. Geographic position of the three western Kenyan counties in the study.

located in Nandi County in the western part of the Rift Valley of Kenya (0°10′0.00″N, 35°08′60.00″E) and was further divided into the following three AEZ: lower highland 1 (LH1), lower highland 2 (LH2) and upper midlands (UM). Details of both sites as well as the sampling protocol have been published in Ndung'u *et al*. (2019). Study site III was located in Bomet county in the southern Rift region of Kenya (0°48′0.00″N, 35°13′59.88″E) and was divided into the following four main AEZ: lower highland 1–3 and upper midlands 1–4. The sample size as well as the sampling protocol in Bomet county closely followed those in the study of Ndung'u *et al*. (2019).

Study sites were in fairly close proximity to one another (Fig. 1), with similar agro-ecological characteristics as described below, and following the characterisation by Jaetzold *et al*. (1983) and a bimodal rainfall pattern, with wet seasons occurring in April–June and October–December (Zhou *et al*. 2007).

Lower highland (LH) has a mean temperature of 15–18°C, altitude range of 1800–2400 m above sea level (asl). Nandi and Bomet covered LH1, which is moderate and humid, with an annual average rainfall of >80% of the potential evaporation, LH2, which is moderate cool and subhumid, with an annual average rainfall of 65–85% of the potential evaporation. Bomet covered LH3, which is moderate cool and semihumid and has an annual average rainfall of 50–65% of the potential evaporation.

Upper midlands (UM) has a mean temperature of 18–21°C and an altitude range of 1300–1900 m asl. Nandi and Bomet covered UM and UM1–4 respectively, while Nyando covered UM2 and UM5. UM1 is temperate and humid, with an annual average rainfall of >85% of the potential evaporation; UM2 is temperate and subhumid, with annual average rainfall of 65–68% of the potential evaporation; UM3 is temperate and semihumid and has an annual average rainfall of 50–65% of the potential evaporation; UM4 is temperate and transitional, with an annual average rainfall of 40–50% of the potential evaporation; and UM5 is temperate and semiarid, with annual average rainfall of 25–40% of the potential evaporation.

Lower midland (LM) has a mean temperature of 21–24°C and an altitude range of 800 to 1500 m asl. Nyando covered LM2, which is warm and subhumid with an annual average rainfall of 65–85% of the potential evaporation.

Goat and sheep feeding and management

Goats and sheep were generally tethered around the homestead during the day, without access to feed supplements, watered by hand and housed in structures made of locally available materials.

(IPCC) Tier II enteric CH_4 estimation: general approach

Total metabolic energy requirements (MER_{Total}) of individual sheep and goats were calculated on a seasonal basis by summing the estimated MER for maintenance (MER_{Mait}), liveweight (LW) gain or loss ($MER_{G/L}$), lactation (MER_L) and locomotion (MER_T). Dry-matter (DM) intake (DMI) was inferred as a function of MER_{Total} and the weighted mean DM digestibility (DMD) of the seasonal feed baskets in each AEZ. DMI was used as the basis for calculation of (DMP: CH_4 g/day).

Animal performance and production data

Data collection closely followed the protocol described in Goopy *et al*. (2018) for cattle, with some modifications for SR. Briefly, animal performance and production data were obtained from measurements of 435, 100 and 199 sheep (734 in total) and 58, 202 and 351 goats (611 in total) in Nandi, Bomet and Nyando respectively. Measurements were undertaken five times (to correspond with the start and finish of each season), over 1 year in each county across all defined AEZ, and formed the dataset for the present study. All sheep and goats present in every household that was part of the study in each county were included. Animals were identified using ear tags (Allflex Europe SA, Vitre, France) with unique numbers, while age was determined by dentition (Cashburn 2016), or by farmer recall for young stock. A portable animal-weighing scale (Model EKW Endeavour Instruments Africa, Nairobi, Kenya) was used to determine LW. Parity and physiological status (pregnant or lactating) was obtained from farmer recall. Measurements were made every 3 months after the initial animal-tagging and data-collection visit, and dates were recorded. Each season was assumed to be of equal duration (i.e. 92 days).

Pasture and fodder yield estimation and analysis

Estimation of fodder and crop residues for Nyando and Nandi study sites have been reported in detail (Goopy *et al*. 2018; Ndung'u *et al*. 2019), and this protocol was repeated for the Bomet study. Briefly, pasture yields and crop residues were estimated using exclusion cages and harvest indexes respectively. Samples of forages and fodder were collected, fresh weights were recorded before samples were oven-dried (50°C, 3–5 days), ground with a hammer-mill, passed through a 1 mm sieve and stored at room temperature in sealed plastic containers until analyses. Nutrient analysis of feed was performed by wet chemistry for DM (AOAC International 2005 (Method 930.15), total N (AOAC Method 990.03), organic matter, neutral detergent fibre and acid detergent fibre (ADF; AOAC Method 973.18) and DMD was estimated from the equation of Oddy *et al*. (1983), as follows:

$$\begin{aligned} \text{DMD (g/100 g DM)} &= 83.58 - 0.824 \times \text{ADF (g/100 g DM)} \\ &\quad + (2.626 \times \text{N (g/100 g DM)}) \end{aligned} \tag{1}$$

MER estimation

Energy expenditure was calculated using equations from Goopy *et al*. (2018), which were transformations of equations published in 'Nutrient Requirements of Domestic Ruminants' (Freer and Nolan 2007) for MER of ruminants. Animal data were analysed by group, based on age and sex; females (>1 year), males (>1 year), juveniles (6–12 months) and kids/lambs (<6 months). Individual MER_M was estimated as follows:

$$\begin{aligned} MER_M(\text{MJ/day}) &= (K \times S \times M(0.26 \times MLW^{0.75}) \\ &\quad \times (\exp(-0.03A)))/((0.02 \times M/D) + 0.5) \end{aligned} \tag{2}$$

where K = 1 (the constant given for sheep and goats), S = 1 for females and 1.15 for males, M = 1, MLW = mean LW for each season, calculated as follows:

$$\text{MLW (kg)} = \frac{\text{start LW (kg) of the season} + \text{end LW (kg) of the season}}{2} \tag{3}$$

where A = age in years and M/D = metabolisable energy content per unit DM (ME MJ/DM kg). M/D was calculated as follows:

$$\text{M/D(MJ/kg)} = 0.172\text{DMD} - 1.707 \tag{4}$$

where DMD = % DMD of feed.

Energy expended for weight gain/loss ($\text{MER}_{\text{G/L}}$) was calculated as follows:

$$\begin{aligned}\text{MER}_{\text{G}}(\text{MJ/day}) = (&\text{ADWG (kg/day)} \times 0.92 \\ &\times \text{EC (MJ/kg))}^{-}(0.043 \times \text{M/D})\end{aligned} \tag{5}$$

$$\begin{aligned}\text{MER}_{\text{L}}(\text{MJ/day}) = (&\text{ADWL}\left(\frac{\text{kg}}{\text{day}}\right) \times 0.92 \\ &\times \text{EC (MJ/kg))}-0.8\end{aligned} \tag{6}$$

where ADWG or ADWL (kg/ day) = average daily weight gain or loss, being the difference between LW at initial season and LW at the end of the season, divided by the number of days in the period; EC (MJ/kg) = energy content of the tissue, taken as a mid-range value of 18 MJ/kg.

Milk production

Farmers typically do not milk their SR, but milk consumption by lambs/kids represents a significant energy impost on their dams. Daily milk consumption of pre-ruminant kids and lambs (DMC, L) was estimated using average LW plus their average daily LW gain (LWG) between 0 and 3.5 months, by extrapolation from Radostits and Bell (1970) as follows:

$$\text{DMC (L)} = (\text{LW (kg)} \times 0.107\text{L/kg}) + \tfrac{3.39\text{ L}}{\text{kg}}\text{LWG} \tag{7}$$

The MER_{L} was calculated by estimating the daily milk yield (MY), as follows:

$$\text{MY (L)} = \text{DCMC (L/day)} \tag{8}$$

MER_{L} was calculated as:

$$\begin{aligned}\text{MER}_{\text{L}}\text{ (MJ/day)} = [&(\text{DMC (L/ day)} \times \text{ECM(MJ/kg))/} \\ &((0.02 \times \text{M/D}) + 0.4)]\end{aligned} \tag{9}$$

where ECM = energy content of milk for sheep and was estimated from the following equation of Brett *et al.* (1972):

$$\text{ECM(MJ)} = 0.0328 \times F + 0.0025D + 2.203 \tag{10}$$

where F = fat content and is assumed to be 80 g/kg, and D = day of lactation, which is assumed to be Day 45, giving a fixed value of 4.94 MJ/ L.

For goats, ECM estimates were based on the work of Morand-Fehr and Sauvant (1980), using the following equation:

$$\text{ECM(MJ)} = 0.0492 \times F + 1309 \tag{11}$$

with an assumed fat content of 35 g/kg, giving a value of 3.03 MJ/L.

Locomotion energy

In contrast to management of cattle, SR were generally maintained around the homestead, often tethered. As such, it was decided to adopt the IPCC default practice of increasing MER_{Mait} by 10% to account for the extra energy expenditure of locomotion.

The daily total energy expenditure ($\text{MER}_{\text{Total}}$) for each animal category in each county and season was then calculated as

$$\begin{aligned}\text{MER}_{\text{TOTAL}}\text{ (MJ/day)} = &\text{MER}_{\text{M}} + \text{MER}_{\text{G/L}} \\ &+ \text{MER}_{\text{L}} + \text{MER}_{\text{T}}(\text{females})\end{aligned} \tag{12}$$

$$\begin{aligned}\text{MER}_{\text{TOTAL}}(\text{MJ/day}) = &\text{MER}_{\text{M}} + \text{MER}_{\text{G/L}} \\ &+ \text{MER}_{\text{T}}(\text{males, heifersandyoungmales})\end{aligned} \tag{13}$$

$$\text{MER(MJ/day)}_{\text{TOTAL}} = \text{MER}_{\text{M}} + \text{MER}_{\text{G/L}}(\text{juveniles}) \tag{14}$$

Daily CH_4 production (DMP) and EF calculation

Dry-matter intake was calculated as follows:

$$\begin{aligned}\text{DMI(kg)} = &\text{MER}_{\text{Total}}(\text{MJ/day})/(\text{GE (MJ/kg)} \\ &\times (\text{DMD}/100))/0.81\end{aligned} \tag{15}$$

where GE = gross energy of the diet, assumed to be 18.1MJ/kg DM, and 0.81 is used as the factor to convert metabolisable energy to digestible energy. The estimated DMI was used to calculate DMP by using the equation developed by Charmley *et al.* (2016), as follows:

$$\text{DMP}\left(\text{g}\,\tfrac{\text{CH4}}{\text{day}}\right) = 20.7 \times \text{DMI (kg/day)} \tag{16}$$

Mean DMP for each class of animal in each season was calculated. In the following, this was used to calculate an annual enteric CH_4 EF (kg CH_4/head.year). DMP for pre-ruminant animals (0–3 months) were excluded from EF calculations for lambs and kids on the assumption that animals at this age produce negligible emissions (Reed *et al.* 1990).

$$\begin{aligned}&\text{EF}\left(\frac{\text{CH4}\,\frac{\text{kg}}{\text{head}}}{\text{year}}\right) \\ &= \frac{\left(\text{DMP}_{\text{wet season 1}} + \text{DMP}_{\text{hot dry season 1}} + \text{DMP}_{\text{wet season 2}} + \text{DMP}_{\text{dry season 2}}\right) \times 365}{4 \times 1000}\end{aligned} \tag{17}$$

Statistical analyses

Descriptive statistics (mean, standard error of the mean (s.e. m.)) were calculated for LW, LW flux, total MER, DMI and DMP for each category, season and AEZ. ANOVA was used to evaluate differences between seasons and location for DMD. Finally, a partial sensitivity analysis was undertaken for some of the key inputs; LW, EC, Ym (CH_4 produced (MJ)/ DMI (MJ)) and DMD were increased by 10%, which was assumed as maximum error margin, and the effect on EF was assessed.

Results

The SR in the study were grouped by species, age and sex as shown in Table 1 (sheep) and Table 2 (goats). Population

Table 1. Sheep population by category (females >1 year (ewes); males >1 year (rams); males and females 6–12 months (young), <6 months (juveniles)) over the four subseasons (rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2), dry season 2 (DS2)) with annual activity (sales, purchases, deaths, births and loans) for three counties, disaggregated by agro-ecological zones (AEZ) in western Kenya

LH, lower highland; UM, upper midlands

County (AEZ)	Animal category	RS1	DS1	RS2	DS2	Sold	Bought	Dead	Relocated	Born	Consumed	Young to adult
Nandi (LH1)	Ewes	63	64	66	62	22	16	0	1	–	3	13
	Rams	19	16	15	12	14	9	0	1	–	1	1
	Young	20	11	6	5	4	6	0	0	–	0	14
	Juvenile	36	62	73	80	25	5	2	0	71	0	0
Nandi (LH2)	Ewes	48	46	49	49	13	10	0	0	–	0	8
	Rams	8	8	5	5	9	2	0	0	–	0	4
	Young	21	9	0	2	8	9	0	0	–	0	12
	Juvenile	35	48	52	59	33	3	1	0	64	1	0
Nandi (UM)	Ewes	19	16	17	13	12	8	0	0	–	0	2
	Rams	3	2	2	2	3	2	0	0	–	0	0
	Young	3	1	0	0	1	0	0	0	–	0	2
	Juvenile	10	13	15	21	4	2	0	0	19	2	0
Nandi (total)	Ewes	130	126	132	124	47	34	0	1	0	3	23
	Rams	30	26	22	19	26	13	0	1	0	1	5
	Young	44	21	6	7	13	15	0	0	0	0	28
	Juveniles	81	123	140	160	62	10	3	0	154	3	0
Bomet (LH1)	Ewes	13	10	10	11	5	2	0	1	–	0	0
	Rams	–	–	–	–	–	–	–	–	–	–	–
	Young	1	2	1	3	0	3	0	1	–	0	0
	Juvenile	7	5	6	7	5	0	1	0	5	0	0
Bomet (LH2)	Ewes	6	4	5	6	7	3	0	0	–	0	2
	Rams	2	1	1	1	3	1	0	0	–	0	0
	Young	2	1	1	1	0	2	0	0	–	0	2
	Juvenile	1	0	2	5	1	0	0	0	5	0	0
Bomet (UM1–4)	Ewes	5	4	4	3	3	0	0	1	–	0	0
	Rams	4	3	3	1	3	2	0	0	–	0	0
	Young	1	1	0	0	0	0	0	0	–	0	1
	Juvenile	2	2	4	4	3	0	0	0	5	0	0
Bomet (LH3)	Ewes	18	20	16	11	13	15	0	1	–	0	1
	Rams	0	1	2	1	1	1	0	0	–	0	1
	Young	1	0	0	0	0	1	0	0	–	0	1
	Juvenile	5	6	6	8	4	2	0	0	7	0	0
Bomet (total)	Ewes	42	38	35	31	28	20	0	3	0	0	3
	Rams	6	5	6	3	7	4	0	0	0	0	1
	Young	5	4	2	4	0	6	0	1	0	0	4
	Juvenile	15	13	18	24	13	2	1	0	22	0	0
Nyando (UM1)	Ewes	15	13	11	10	6	1	0	0	–	–	–
	Rams	9	6	2	1	7	2	0	0	–	–	–
	Young	5	4	8	8	11	7	0	0	–	–	–
	Juvenile	16	24	25	22	8	0	0	0	17	–	–
Nyando (UM5)	Ewes	19	24	24	21	13	10	0	0	–	–	–
	Rams	6	3	1	1	5	1	0	0	–	–	–
	Young	16	14	12	8	7	8	0	0	–	–	–
	Juvenile	26	39	34	30	18	2	0	0	30	–	–
Nyando (LM2)	Ewes	42	39	37	34	30	13	0	0	–	–	–
	Rams	8	2	2	2	6	0	0	0	–	–	–
	Young	17	20	22	19	9	17	0	0	–	–	–
	Juvenile	44	48	60	52	23	10	0	0	37	–	–
Nyando (total)	Ewes	76	76	72	65	49	24	0	0	0	–	–
	Rams	23	11	5	4	18	3	0	0	0	–	–
	Young	38	38	42	35	27	32	0	0	0	–	–
	Juvenile	86	111	119	104	49	12	0	0	84	–	–

Table 2. Goat population by category (females >1 year (does), males >1 year (bucks), males and females 6–12 months (young), <6 months (juveniles)) over the four subseasons (rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2), dry season 2 (DS2)) with annual activity (sales, purchases, deaths, births and loans) for three counties, disaggregated by agro-ecological zones (AEZ) in western Kenya

F, female; M, male; LH, lower highland; UM, upper midlands

County (AEZ)	Animal category	RS1	DS1	RS2	DS2	Sold	Bought	Dead	Relocated	Born	Consumed	Young to adult
Nandi (LH1)	Does	12	4	3	3	8	0	0	1	–	0	0
	Bucks	1	3	2	1	3	1	0	0	–	0	1
	Young M and F	2	0	0	0	2	0	0	0	–	0	0
	Juveniles	5	5	4	5	2	1	0	0	1	0	0
Nandi (LH2)	Does	8	5	7	7	0	2	0	0	–	0	0
	Bucks	0	0	0	0	–	–	–	–	–	–	–
	Young M and F	3	2	1	1	1	1	0	0	–	0	1
	Juveniles	2	2	5	4	2	1	0	0	4	0	0
Nandi (UM)	Does	5	8	6	5	3	1	0	1	–	0	0
	Bucks	0	0	1	1	0	0	0	0	–	0	1
	Young M and F	4	3	1	1	1	1	0	0	–	0	1
	Juveniles	4	2	3	3	1	0	0	2	3	0	0
Total Nandi	Does	25	17	16	15	11	3	0	2	0	0	0
	Bucks	1	3	3	2	3	1	0	0	0	0	2
	Young M and F	9	5	2	2	4	2	0	0	0	0	2
	Juveniles	11	9	12	12	5	2	0	2	8	0	0
Bomet (LH1)	Does	1	1	1	1	0	0	0	0	–	0	0
	Bucks	1	1	0	0	1	1	0	0	–	0	0
	Young M and F	–	–	–	–	–	–	–	–	–	–	–
	Juveniles	1	1	3	3	0	0	0	0	3	0	0
Bomet (LH2)	Does	5	7	8	8	2	3	0	0	–	0	1
	Bucks	0	1	1	0	1	1	0	0	–	0	0
	Young M and F	2	3	3	4	3	2	0	0	–	0	1
	Juveniles	5	5	12	11	6	1	0	0	9	0	0
Bomet (UM1–4)	Does	22	23	21	10	17	6	0	0	–	0	0
	Bucks	4	4	3	2	2	1	0	0	–	0	0
	Young M and F	0	1	1	0	1	1	0	0	–	0	0
	Juveniles	11	16	15	8	18	1	0	0	15	0	0
Bomet (LH3)	Does	39	37	37	35	14	11	0	1	–	0	1
	Bucks	4	1	4	4	5	3	0	0	–	0	1
	Young M and F	13	13	15	9	13	11	0	0	–	0	2
	Juveniles	17	25	37	35	13	3	0	0	26	0	0
Total Bomet	Does	67	68	67	54	33	20	0	1	0	0	2
	Bucks	9	7	8	6	9	6	0	0	0	0	1
	Young M and F	15	17	19	13	17	14	0	0	0	0	3
	Juveniles	34	47	67	57	37	5	0	0	53	0	0
Nyando (UM1)	Does	5	5	3	3	2	3	0	0	–	–	–
	Bucks	1	1	2	2	1	2	0	0	–	–	–
	Young M and F	2	2	2	1	1	0	0	0	–	–	–
	Juveniles	2	1	3	3	4	0	0	0	3	–	–
Nyando (UM5)	Does	55	49	44	31	25	14	0	0	–	–	–
	Bucks	7	6	3	2	5	0	0	0	–	–	–
	Young M and F	10	7	5	2	8	1	0	0	–	–	–
	Juveniles	24	38	41	36	24	0	0	0	39	–	–
Nyando (LM2)	Does	21	17	12	8	9	3	0	0	–	–	–
	Bucks	4	0	4	4	3	2	0	0	–	–	–
	Young M and F	5	0	0	0	3	0	0	0	–	–	–
	Juveniles	16	8	12	2	13	0	0	0	10	–	–
Total Nyando	Does	81	71	59	42	36	20	0	0	0	–	–
	Bucks	12	7	9	8	9	4	0	0	0	–	–
	Young M and F	17	9	7	3	12	1	0	0	0	–	–
	Juveniles	42	47	56	41	41	0	0	0	52	–	–

demographics varied between and within counties with the largest number of sheep found in Nandi, while goats predominated in Nyando, with mature females always the most numerous class for both species in all areas. This pattern was independent of season, nonetheless numbers declined across seasons due to sales and domestic consumption. Over 50% of mature females gave birth throughout the year (with a low level of twinning – not reported), while reported mortality was low (<1%) for all classes of both sheep and goats.

The mean LW for each animal class fluctuated across AEZ, counties and seasons for both sheep and goats (refer Tables S1–S4, available as Supplementary Material to this paper) for data disaggregated by AEZ) and is shown for Nandi county in Table 3 (sheep) and Table 4 (goats).

There was some seasonal fluctuation in the LW of mature stock of both species; however young stock and juveniles of both species showed strong LWG season on season, although trends varied between county and AEZ (as shown in Tables S5–S8). This is also reflected in LW change across seasons for the different classes of stock, with young stock and juveniles showing consistent LWGs (Tables 5, 6).

Detailed analysis of the weighted feed basket has been reported elsewhere for Nyando (Onyango *et al*. 2019), Nandi (Ndung'u *et al*. 2019) and Bomet (Table S9; Ndung'u, Goopy, Onyango, unpubl. data). Summary data for the weighted DMD of the seasonal feed basket is presented in Table 7. The DMD varied between seasons, AEZs and counties, but was in a fairly narrow range of 56–68%, with the Nyando sites tending to

Table 4. Seasonal liveweight (mean ± s.e.m., kg) for goats males (bucks) and females (does) >1 year, young males and females 6 months to year (young) and juveniles (<6 months) over the rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2), dry season 2 (DS2), disaggregated by agro-ecological zones (AEZ) in Nandi county, Kenya

–, no animals present in that AEZ and season

AEZ	RS1	DS1	RS2	DS2
		Does		
Lower highland 1	22.9 ± 2.26	29.1 ± 3.46	29.0 ± 5.39	28.2 ± 4.99
Lower highland 2	23.2 ± 1.79	27.4 ± 2.16	25.6 ± 2.09	24.7 ± 1.75
Upper midlands	20.5 ± 1.99	20.5 ± 1.65	19.7 ± 1.57	22.3 ± 1.47
Mean	22.2 ± 1.29	24.5 ± 1.54	24.0 ± 1.63	24.6 ± 1.35
		Bucks		
Lower highland 1	48 ± 0.00	38.3 ± 6.20	37.2 ± 9.35	50.2 ± 0.00
Lower highland 2	–	–	–	–
Upper midlands	–	–	18.8 ± 0.00	21.8 ± 0.00
Mean	48.0 ± 0.00	38.3 ± 6.20	31.0 ± 8.16	36.0 ± 14.20
		Young		
Lower highland 1	14.5 ± 3.10	–	–	–
Lower highland 2	15.7 ± 2.76	15.8 ± 3.60	21.8 ± 0.00	23.5 ± 0.00
Upper midlands	10.2 ± 1.99	14.2 ± 1.08	12.9 ± 0.00	14.1 ± 0.00
Mean	13.0 ± 1.54	14.8 ± 1.34	17.4 ± 4.45	18.8 ± 4.70
		Juveniles		
Lower highland 1	11.8 ± 0.47	13.5 ± 0.63	15.1 ± 1.41	14.3 ± 1.80
Lower highland 2	14.4 ± 2.25	18.2 ± 0.40	9.7 ± 2.37	11.0 ± 1.08
Upper midlands	9.4 ± 0.59	10.0 ± 1.55	8.1 ± 2.89	12.1 ± 2.38
Mean	11.4 ± 0.70	13.8 ± 1.07	11.1 ± 1.48	12.7 ± 1.03

Table 3. Seasonal liveweight (mean ± s.e.m., kg) for sheep males (rams) and females (ewes) >1 year, young males and females 6–12 months (young) and juveniles (<6 months) over the rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2), dry season 2 (DS2), disaggregated by agro-ecological zones (AEZ) in Nandi county, Kenya

–, no animals present in that AEZ and season

AEZ	RS1	DS1	RS2	DS2
		Ewes		
Lower highland 1	34.2 ± 1.04	34.5 ± 0.99	32.8 ± 0.88	33.1 ± 0.98
Lower highland 2	31.3 ± 1.03	31.4 ± 1.00	30.7 ± 0.94	32.8 ± 0.98
Upper midlands	30.5 ± 2.05	31.9 ± 1.88	29.8 ± 1.79	28.9 ± 1.88
Mean	32.6 ± 0.71	33.1 ± 0.67	31.6 ± 0.61	32.5 ± 0.66
		Rams		
Lower highland 1	34.1 ± 2.15	35.6 ± 2.01	37.6 ± 1.96	41.1 ± 2.56
Lower highland 2	33.9 ± 4.61	34.4 ± 3.51	36.4 ± 5.25	39.5 ± 5.79
Upper midlands	32.8 ± 12.61	47.0 ± 12.15	46.5 ± 13.70	21.3 ± 0.00
Mean	33.9 ± 2.07	36.1 ± 1.85	38.1 ± 2.02	39.5 ± 2.49
		Young		
Lower highland 1	24.1 ± 1.84	27.3 ± 2.64	29.0 ± 4.28	33.6 ± 4.81
Lower highland 2	24.0 ± 1.74	24.3 ± 0.67	–	34.4 ± 2.20
Upper midlands	16.8 ± 3.04	15.0 ± 0.00	–	–
Mean	23.6 ± 1.21	25.4 ± 1.43	29.0 ± 4.28	33.8 ± 3.36
		Juveniles		
Lower highland 1	14.7 ± 1.24	15.8 ± 1.12	17.4 ± 1.00	17.9 ± 0.97
Lower highland 2	12.3 ± 0.83	14.4 ± 1.08	16.4 ± 1.08	15.7 ± 0.98
Upper midlands	7.0 ± 1.50	10.4 ± 1.26	12.7 ± 1.31	11.8 ± 1.35
Mean	13.0 ± 0.72	14.7 ± 0.73	16.6 ± 0.68	16.3 ± 0.65

Table 5. Seasonal average daily gain (mean ± s.e.m., g/day) for sheep males (rams) and females (ewes) >1 year, young males and females, 6–12 months (young) and juveniles (<6 months) across rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2) and dry season 2 (DS2) in the three agro-ecological zones (AEZ) in Nandi county

–, no animals present in that AEZ and season

AEZ	RS1	DS1	RS2	DS2
		Ewes		
Lower highland 1	25.8 ± 9.06	–20.8 ± 10.11	–10.7 ± 7.33	20.3 ± 7.55
Lower highland 2	24.0 ± 7.35	–27.4 ± 8.68	23.9 ± 6.69	11.7 ± 6.66
Upper midlands	4.4 ± 13.33	–25.1 ± 13.66	–18.1 ± 9.14	–2.1 ± 18.12
All	23.3 ± 5.55	–23.9 ± 6.16	2.4 ± 4.87	14.7 ± 4.92
		Rams		
Lower highland 1	22.1 ± 23.73	54.9 ± 13.32	31.1 ± 12.37	48.8 ± 10.19
Lower highland 2	36.7 ± 10.00	13.0 ± 3.76	43.0 ± 11.65	45.1 ± 19.54
Upper midlands	0.00 ± 0.00	24.2 ± 0.00	-43.5 ± 0.00	–215.9 ± 0.00
All	25.3 ± 18.33	42.5 ± 10.24	30.1 ± 9.76	25.8 ± 23.33
		Young		
Lower highland 1	48.6 ± 11.97	44.0 ± 17.09	33.1 ± 22.62	38.2 ± 17.87
Lower highland 2	46.6 ± 10.03	37.2 ± 10.07	–	–
Upper midlands	24.4 ± 0.00	35.2 ± 0.00	–	–
All	46.1 ± 8.13	40.5 ± 9.44	5.9 ± 31.52	38.2 ± 17.87
		Juveniles		
Lower highland 1	94.4 ± 14.04	58.4 ± 12.69	77.3 ± 9.92	63.1 ± 5.75
Lower highland 2	120.1 ± 10.77	76.1 ± 9.50	86.5 ± 9.39	67.2 ± 7.63
Upper midlands	57.8 ± 2.22	62.5 ± 16.75	40.5 ± 11.26	29.2 ± 8.07
All	100.3 ± 9.62	65.4 ± 7.60	75.6 ± 6.52	60.2 ± 4.29

Table 6. Seasonal average daily gain (mean ± s.e.m., g/day) for goat males (bucks) and females (does) >1 year, males and females 6–12 months (young) and juveniles (<6 months) across rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2) and dry season 2 (DS2) in the three agro-ecological zones in Nandi county, Kenya

–, no animals present in that AEZ and season

AEZ	RS1	DS1	RS2	DS2
		Does		
Lower highland 1	10.8 ± 12.81	–3.6 ± 11.66	6.5 ± 23.01	–27.2 ± 34.11
Lower highland 2	35.1 ± 18.56	52.3 ± 13.36	–42.2 ± 13.45	11.4 ± 7.22
Upper midlands	11.7 ± 13.81	17.6 ± 15.29	3.9 ± 10.09	36.6 ± 8.47
All	18.8 ± 8.66	26.1 ± 9.97	–13.2 ± 10.02	12.1 ± 9.32
		Bucks		
Lower highland 1	–40.8 ± 0.00	40.0 ± 0.00	80.5 ± 0.00	–
Lower highland 2	–	–	–	–
Upper midlands	–	–	13.0 ± 0.00	58.5 ± 0.00
All	–40.8 ± 0.00	40.0 ± 0.00	46.7 ± 0.00	58.5 ± 0.00
		Young		
Lower highland 1	–	–	–	–
Lower highland 2	64.8 ± 28.57	40.0 ± 0.00	1300 ± 0.00	25.9 ± 0.00
Upper midlands	15.3 ± 4.15	41.3 ± 0.00	–10.9 ± 0.00	43.0 ± 0.00
All	40.0 ± 18.52	40.7 ± 0.65	1.1 ± 11.96	34.5 ± 8.58
		Juveniles		
Lower highland 1	19.0 ± 15.58	25.5 ± 9.45	1.6 ± 12.47	17.5 ± 23.87
Lower highland 2	123.5 ± 0.00	26.7 ± 0.00	–	84.1 ± 15.14
Upper midlands	31.1 ± 0.00	32.6 ± 0.00	17.4 ± 0.00	85.3 ± 16.03
All	38.5 ± 19.80	26.9 ± 3.09	4.8 ± 10.16	64.5 ± 13.81

Table 7. Seasonal (rainy season 1 (RS1), dry season 1 (DS1), rainy season 2 (RS2), dry season 2 (DS2)) dry-matter digestibility (DMD) in three counties, disaggregated by agro-ecological zones (AEZ) in western Kenya

		% DMD			
Study site	AEZ	RS1	DS1	RS2	DS2
Nandi	Lower highland 1	63.4	63.4	65.6	68.3
	Lower highland 2	60.3	60.3	65.1	66.0
	Upper midlands	64.2	64.2	60.1	60.4
Bomet	Lower highland 1	61.7	61.5	62.6	63.1
	Lower highland 2	61.0	60.5	61.9	62.1
	Lower highland 3	62.9	61.8	64.1	64.1
	Upper midlands 1–4	61.1	61.8	63.3	61.6
Nyando	Upper midland 1	59.6	58.7	59.3	56.2
	Upper midland 5	59.2	60.0	57.7	57.7
	Lower midland 2	63.8	64.1	55.9	56.8

Table 8. Emission factors (mean ± s.e.m., kg CH_4/head.year) for sheep females (ewes) >1 year, males (rams) and young males and females, 6–12 months (young) and juveniles (<6 months) in Nandi, Bomet and Nyando counties of Kenya, disaggregated by agro-ecological zone (AEZ)

–, no animals present in that AEZ and season

AEZ or study site	Ewes	Rams	Young	Juveniles
		Nandi		
Lower highland 1	4.6 ± 0.20	5.1 ± 0.35	4.6 ± 0.53	4.6 ± 0.33
Lower highland 2	5.1 ± 0.28	5.1 ± 0.58	4.2 ± 0.20	4.6 ± 0.37
Upper midlands	4.0 ± 0.32	3.4 ± 0.00	3.2 ± 0.00	3.2 ± 0.48
Mean	4.7 ± 0.16	5.0 ± 0.32	4.4 ± 0.41	4.4 ± 0.23
		Bomet		
Lower highland 1	5.2 ± 0.54	–	5.6 ± 0.00	4.6 ± 1.04
Lower highland 2	4.4 ± 0.56	4.1 ± 0.00	4.3 ± 0.00	6.4 ± 0.00
Lower highland 3	5.9 ± 1.03	5.5 ± 0.00	8.9 ± 0.00	5.9 ± 0.00
Upper midlands 1–4	4.1 ± 0.35	5.5 ± 0.00	2.7 ± 0.00	4.5 ± 1.12
Mean	4.7 ± 0.30	5.2 ± 1.03	4.5 ± 0.94	4.9 ± 0.70
		Nyando		
Highlands	4.6 ± 0.53	3.2 ± 0.00	3.9 ± 0.00	1.9 ± 0.00
Lowlands	4.1 ± 0.24	3.7 ± 0.67	3.6 ± 0.58	2.7 ± 0.30
Slopes	4.4 ± 0.39	4.4 ± 0.36	2.8 ± 0.06	2.8 ± 0.48
Mean	4.2 ± 0.20	3.7 ± 0.38	3.6 ± 0.39	2.6 ± 0.26

Table 9. Emission factors (mean ± s.e.m., kg CH_4/head.year) for goat males (bucks) and females (does) >1 year, males and females 6–12 months (young) and juveniles (<6 months) in Nandi, Bomet and Nyando counties of Kenya, disaggregated by agro-ecological zone (AEZ)

–, no animals present in that AEZ and season

AEZ or study site	Does (>1year)	Bucks (>1year)	Young males and females (6 months to 1 year)	Juveniles (<6 months)
		Nandi		
Lower highland 1	3.3 ± 0.47	5.0 ± 0.00	2.2 ± 0.09	2.7 ± 0.42
Lower highland 2	4.2 ± 0.43	–	3.7 ± 0.00	3.3 ± 0.00
Upper midlands	3.5 ± 0.31	2.0 ± 0.00	2.7 ± 0.00	3.1 ± 0.00
Mean	3.6 ± 0.28	4.7 ± 0.00	3.1 ± 0.47	3.0 ± 0.32
		Bomet		
Lower highland 1	4.3 ± 0.00	3.6 ± 0.00	–	2.6 ± 0.00
Lower highland 2	3.9 ± 0.52	3.5 ± 0.00	3.4 ± 0.41	3.8 ± 0.00
Lower highland 3	3.9 ± 0.35	4.8 ± 0.60	3.1 ± 0.00	2.5 ± 0.71
Upper midlands 1–4	4.2 ± 0.32	4.4 ± 0.00	3.3 ± 0.39	3.9 ± 0.43
Mean	4.1 ± 0.22	4.4 ± 0.41	3.3 ± 0.31	3.5 ± 0.35
		Nyando		
Highlands	4.0 ± 0.35	3.7 ± 0.00	2.9 ± 0.30	3.1 ± 0.31
Lowlands	3.2 ± 0.21	3.7 ± 0.00	3.3 ± 0.28	3.0 ± 0.25
Slopes	3.8 ± 0.24	4.9 ± 0.32	3.3 ± 0.29	3.1 ± 0.22
Mean	3.6 ± 0.16	4.2 ± 0.43	3.2 ± 0.19	3.0 ± 0.15

have lower DMD in feed across seasons than did either Nandi or Bomet.

Young and juvenile sheep in both Bomet and Nandi had calculated EF approaching those of adult ewes and rams, this being underpinned by the high weight gains (70–135 g/day), driving MER, intake and, ultimately, DMP. While EF for goats of all classes were lower than those for sheep, they followed the same trend as the values for young, growing stock, namely, being similar to those of adults (Tables 8, 9).

Population-weighted mean LWs and EF for sheep and goats in the three counties (Table 10) showed that the influence of young stock dominating flock numbers tends to produce lower mean LWs across the regions. Additionally, the high growth rates observed in young stock, possibly the cumulative effect of management and nutrition, effectively lift EF of growing animals close to that of mature adults.

Increasing DMD (by 10%) reduced the mean EF by 12.9%, while the effect of increasing Ym was strictly proportional.

In contrast, increasing LW increased EF by 5.7%, while increasing the EC of tissue for growth increased the EF by 0.11% on average.

Discussion

The EF developed for SR in the present study are similar for sheep (~4.4 kg vs 5.0 kg CH_4/year), but substantially smaller for goats (3.7 vs 5 kg CH_4/year) than those of the IPCC Tier I EF for SR in developing countries (Dong *et al*. 2006). This was unsurprising, given that MER_{Mait} tends to be the largest determinant of overall energy requirements in smallholder systems (Goopy *et al*. 2018), which, in turn, is proportional to LW, which strongly influences intake. This is also reflected in EF developed for SR in other studies, especially when compared with IPCC default values (Table 11). Generally, such studies have employed a combination of census or informal data collection with a (IPCC) Tier I or modified Tier II approaches (e.g. Defar *et al*. 2018; Svinurai *et al*. 2018). However, heterogeneity and seasonality of feed supply are hallmarks of livestock raising in the rain-fed smallholder farming of East Africa, which these approaches arguably fail to capture. The present study was designed to take account of this variability, but comes with its own potential limitations. Developing a framework to estimate intake from energy expenditure in SR (Freer and Nolan 2007) that is not based specifically on data from African livestock, has unknown implications, but represents the best and most relevant knowledge available at present. The validity of using an Ym derived from Australian cattle is open to disputation; however, there were good reasons for this decision. First, the constant (Ym = 6.3%) was derived from a large dataset of ruminant measurements (albeit cattle) consuming mainly C3 and C4 grasses (while, to our knowledge, no such study is available for SR), thus representing a fairly good match for ruminants in the present study, whose principal diet was C4 grasses. Second, the constant of Charmley *et al*. (2016) is in close agreement with the IPCC Ym for both cattle and sheep (6.5%; Dong *et al*. 2006) and is very similar to the value for sheep developed from a large literature (6.54%) by Patra *et al*. (2016). Finally, in their evaluation of the precision of numerous equations to predict enteric CH_4 production from feed intake (and constituents), Benaouda *et al*. (2019) reported moderately large errors of prediction in all equations. Thus, it appears unlikely that any predictive equation will provide a high degree of accuracy in estimating DMP from feed. It is of concern that recently published work has determined that low levels of feeding in cattle substantially increase Ym over *ad libitum* levels of intake (Goopy *et al*. 2020). If demonstrated for SR, this would have important implications for inventory calculations, as well as presenting the challenge of applying an 'inconstant constant' to enteric CH_4 calculations.

Sensitivity analysis showed the influence of feed digestibility on EF, but this is, in part, due to presumptive intake being driven by energy expenditure, with more digestible feeds providing greater digestible energy and, hence, lowering intake (and emissions). Physiologically, this appears to be incorrect, as, in practice, an animal would

Table 10. Weighted mean liveweight (kg) and emission factor (CH_4 kg/year) for all sheep and goats in Nandi, Bomet and Nyando counties in western Kenya

Study site	Species	Weighted liveweight (kg)	Weighted emission factor (kg CH_4/head.year)
Nandi	Sheep	25.2	4.6
	Goat	20.2	3.4
Bomet	Sheep	27.3	4.8
	Goat	20.9	3.8
Nyando	Sheep	18.3	3.8
	Goat	18.4	3.7

Table 11. Enteric methane emission factor and liveweight for sheep and goats from different locations in Sub-Saharan Africa

Study	Region	Species	Emission factor (kg CH_4/head.year)	Liveweight (kg)
Dong *et al*. (2006)	Developing countries IPCC estimates	Sheep	5.0	45.0
Du Toit *et al*. (2013)	South Africa	Sheep (communal)	6.1	42.5
Ndao *et al*. (2019)	West Africa	Sheep	2.3	17.1
Present study	Nandi	Sheep	4.6	25.2
Present study	Bomet	Sheep	4.8	27.3
Present study	Nyando	Sheep	3.8	18.3
Present study	Kenya	Sheep	4.4	23.7
Dong *et al*. (2006)	Developing countries IPCC estimates	Goat	5.0	40.0
Du Toit *et al*. (2013)	South Africa	Goats (communal)	6.3	46.5
Ndao *et al*. (2019)	West Africa	Goat	2.3	14.2
Present study	Nandi	Goat	3.4	20.2
Present study	Bomet	Goat	3.8	20.9
Present study	Nyando	Goat	3.7	18.4
Present study	Kenya	Goat	3.7	19.3

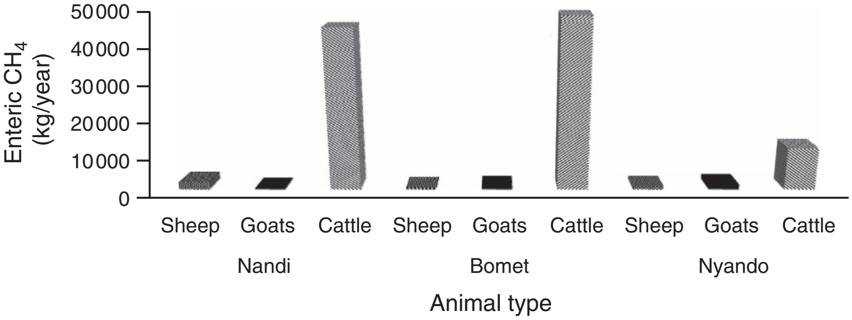

Fig. 2. Contribution of sheep, goats and cattle to total annual enteric methane emissions (CH4 kg/year) of surveyed herds in Nandi, Bomet and Nyando counties in western Kenya.

normally be expected to eat more, not less, of a more digestible food. However, these assumptions are needed to account for variations in intake in an environment where feeding is highly variable and even access to feed is frequently limited.

We compared the total enteric CH_4 emissions of SR in these areas with the total emissions of cattle from previously published studies (Goopy *et al*. 2018; Ndung'u *et al*. 2019) to assess the relative importance of SR to overall livestock enteric emissions (Fig. 2). In contrast to published estimates, we found that SR contributed only ~5% of the estimated emissions Thus, it is clear, that at least in the areas studied, the contribution of SR to enteric CH_4 emissions is much smaller than that of cattle (Fig. 2), both due to lower numbers and per capita biomass. In this respect, our findings were not dissimilar to those of recent studies in Ethiopia, which attributed 92% of total livestock GHG emissions to cattle (Defar *et al*. 2018). These results suggest that current modelling and estimates may overstate the importance of the contribution of SR to total livestock emissions in SSA (Herrero *et al*. 2008; Herrero *et al*. 2013), which suggest 15–25% of livestock-generated GHG across Africa are attributable to sheep and goats.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This research was conducted as part of the CGIAR Research Program on Livestock and is supported by contributors to the CGIAR Trust Fund. CGIAR (www.cgiar.org) is a global research partnership for a food-secure future. Its science is conducted by 15 Research Centers in close collaboration with hundreds of partners across the globe.

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Handling editor: Ermias Kebreab