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Corrigendum

Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of Nandi County, Kenya

P. W. Ndung'u, B. O. Bebe, J. O. Ondiek, K. Butterbach-Bahl, L. Merbold and J. P. Goopy

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The authors regret that a recent examination of their data for other purposes has led to the discovery of an error in the calculation of the metabolic energy requirement for maintenance (MER_M) in the original calculations of this article. This was occasioned by the application of an incorrect constant to the calculation of MER_M to male animals >2 years, male animals 1–2 years and calves and had the effect of increasing the emission factors (EFs) for these classes of animals by 3–29%. Table 5 with the corrected EFs for all classes of animal is shown below.

Table 5. Emission factors (mean ± s.e.m., kg methane (CH_4)/head.year) for females and males (>2 years), heifers and young males (1–2 years), and calves (<1 year) in the three agro-ecological zones (lower highland 1, lower highland 2, upper midlands) of Nandi County, Kenya

Agro-ecological zone	Emission factors (kg CH_4/head.year)				
	Females (>2 years)	Males (>2 years)	Heifers (1–2 years)	Young males (1–2 years)	Calves (<1 year)
Lower highland 1	48.7 ± 1.28	33.2 ± 2.96	28.7 ± 0.94	26.5 ± 1.24	26.1 ± 0.93
Lower highland 2	52.6 ± 3.01	42.1 ± 3.13	27.9 ± 1.84	28.7 ± 2.57	25.3 ± 1.82
Upper midlands	45.7 ± 2.68	35.2 ± 2.08	27.8 ± 2.30	27.8 ± 2.83	25.4 ± 2.49
Total Nandi	47.8 ± 2.75	37.2 ± 4.55	28.5 ± 2.18	27.2 ± 3.13	25.8 ± 2.18

The authors emphasise that this does not affect the text or the formulae given in the article, as these were correct. The authors apologise for any inconvenience caused.

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Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of Nandi County, Kenya

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Abstract. National greenhouse-gas (GHG) inventories in most developing countries, and in countries in Sub-Saharan Africa in particular, use default (Tier I) GHG emission factors (EFs) provided by the Intergovernmental Panel on Climate Change (IPCC) to estimate enteric methane (CH_4) emissions from livestock. Because these EFs are based on data primarily from developed countries, there is a high degree of uncertainty associated with CH_4 emission estimates from African livestock systems. Accurate Tier II GHG emission reporting from developing countries becomes particularly important following the Paris Climate agreement made at COP21, which encourages countries to mitigate GHG emissions from agricultural sources. In light of this, the present study provides improved enteric CH_4 emission estimates for cattle in Nandi County, Western Kenya, representing a common livestock production system found in East Africa. Using the data from measurements of liveweight and liveweight change, milk production and locomotion collected from 1143 cattle in 127 households across 36 villages over three major agro-ecological zones covering a full year, we estimated total metabolic energy requirements. From this and assessments of digestibility from seasonally available feeds, we estimated feed intake and used this to calculate daily CH_4 production by season, and, subsequently, created new EFs. Mean EFs were 50.6, 45.5, 28.5, 33.2 and 29.0 kg CH_4/head.year for females (>2 years), males (>2 years), heifers (1–2 years), young males (1–2 years) and calves (<1 year) respectively, and were lower than the IPCC Tier I estimates for unspecified African adult cattle, but higher for calves and young males. Thus, using IPCC Tier 1 EFs may overestimate current enteric CH_4 emissions in some African livestock systems.

Additional keywords: Africa, cattle, dry matter digestibility, feed basket, greenhouse gas, liveweight.

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Introduction

Methane emissions from enteric fermentation have been identified as a key source of greenhouse-gas emissions (GHG) from agricultural sources in developing countries (Tran *et al.* 2011). This is because most developing countries depend largely on the agricultural sector for economic production and development, with livestock-related emissions, specifically enteric fermentation, dominating national GHG emission inventories. The Intergovernmental Panel on Climate Change (IPCC) has developed three different approaches for estimating enteric methane (CH_4) emissions. Tier I estimates use default emission factors (EFs) developed to represent the GHG emissions from livestock systems in different geographic regions on the basis of livestock census data and assumptions regarding the systems themselves (Spurlock *et al.* 2012). It is recognised that Tier I estimates have shortcomings, both because they are derived from data from livestock systems in developed economies ('adjusted' to fit the conditions of developing countries) and by their nature, as the approach cannot accommodate changes to emissions brought about by changes to livestock production systems. Tier II estimates can represent a substantial increase in the precision of CH_4 emissions from livestock because they better define animals, productivity, management and feed through using actual measurements of these characteristics (Tubiello *et al.* 2013).

Kenya's agricultural sector accounts for 58.6% of the country's total GHG emissions (the largest emitter) and emissions related to livestock production account for 96.2% of agricultural emissions (Tubiello *et al.* 2014). The bulk of these emissions can be attributed to the 1.8 million smallholder dairy farms owning ~2.64 million dairy cattle, producing an estimated 2.5 million tonnes of raw milk annually (80% of marketed milk; Methu *et al.* 2001; Waithaka *et al.* 2002; Orodho 2006). Animals in smallholder systems are generally offered feeds low in digestibility and protein, which are associated with higher enteric CH_4 emissions per kilogram dry-matter intake (DMI).

The IPCC good-practice guidelines state that Tier II approaches should be used for key national GHG sources (Spurlock *et al.* 2012), i.e. such source categories that have a significant influence on a country's GHG inventory in terms of the absolute level of emissions, the trend in emissions, or both (e.g. in the case of Kenya, where ruminant CH_4 emissions represent a large proportion of the country's total GHG emissions). In light of the forgoing, it is important to develop country-specific Tier II EFs for Kenya and other countries in Sub-Saharan Africa with a significant livestock population, so as to be able to quantify the effect of future interventions on baseline emissions. A recent study in Nyando Province Kenya developed Tier II enteric CH_4 EFs for cattle using measured livestock and feed-characteristic data (Gordon and Illius 1994). The findings demonstrated clear differences between (default) Tier I estimates and the Tier II estimates developed in the study. As such, findings cannot be extrapolated to a national or even regional level without further corroboration; there is a strong need for further region-specific livestock and feed data to facilitate the development of Tier II enteric CH_4 EFs on a wider scale. In the present study, we hypothesised that the (Tier II) EFs we derived in Nandi County would not be different from those derived from the study in Nyando (Goopy *et al*. 2018), as both regions have broadly comparable livestock systems characterised by small land areas, low numbers of livestock per household and low farm inputs, and are located in the western highlands of Kenya.

Materials and methods

Site selection

The study site (Nandi County) is located in the western part of the Rift Valley of Kenya. According to the Kenya zoning system, Nandi County falls under Zone III, which has an annual rainfall of 950–1500 mm and the climate and soils are highly suitable for agricultural cultivation, so that the county is densely populated by smallholders (Waghorn and Clark 2004). This site was chosen because of the current and growing importance of dairying in the local economy. The sampling protocol (J. Owino, pers. comm.) started with a participatory mapping exercise conducted using expert knowledge of personnel from the International Livestock Research Institute and Nandi County government. In Nandi County, the following three agro-ecological zones (AEZs) were identified on the basis of altitude, rainfall and temperature and predominant land use: lower highland 1 (LH1: 1900–2400 m above sea level), lower highland 2 (LH2: 1400–1900 m above sea level) and upper midlands (UM: 1200–1400 m above sea level; GoK 2013). The number of sampling points in each AEZ was based on the total sample size (~120 households) weighted by the total area of each AEZ. In total, 36 GPS points across the three AEZs were selected, restricted by proximity to roads of 2 km (<2 km distant). GPS points were allocated across the three AEZs (LH1: 22, LH2: 8 and UM: 6) and then used to navigate to the nearest village, where three to four farmers were selected with the assistance from local administration and recruited during the initial household visit.

Animal feeding/grazing management

In the study area, most animals were kept at pasture, grazing most of the day (from ~0730 hours to 1500 hours) for those accessing water around the homestead (mainly LH1 zone). Stock watered at rivers/streams grazed for a shorter time period (~2 h shorter), but also accessed roadside grazing as they returned to the homestead (predominantly in LH2). Cut and carry feeding was practiced in the evening, with females offered limited amounts of Napier and/or Rhodes (cv. Boma) grass after milking. Supplementary morning feeding was less common, especially during the dry season. Animals were also let graze stover in maize fields after harvest. Herding was common in the UM zone where most animals were grazed by the roadside and in harvested sugarcane fields between 0700 hours and 1700 hours. Stock were universally corralled in bomas (stockyards) overnight (1800 hours to 0700 hours), usually without access to feed or water.

(IPCC) Tier II enteric CH_4 estimation: general approach

Total metabolic energy requirements (MER_{Total}) of individual cattle on a seasonal basis were calculated by summing the estimated MER for maintenance (MER_M), LW gain or loss ($MER_{G/L}$), lactation (MER_L) and locomotion/traction (MER_T). 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 daily CH_4 production rate (MPR).

Animal performance and production data

Data collection followed the protocol described in Goopy *et al*. (2018), but briefly, animal performance and production data from measurements of 1143 cattle in the three AEZs formed the basis of the present study and all cattle present in each household during the survey were included. During the second household visit (the first having been to identify participants), animals were identified using ear tags (Allflex Europe SA, Vitre, France) with unique numbers. Age was determined by dentition (Torell *et al.* 1998) or by farmer recall for young cattle. A portable animal-weighing scale (Model EKW Endeavour Instrument Africa Ltd, Nairobi, Kenya) was used to determine LW. Heart girth was measured using a heart-girth measuring tape. Body condition scoring was assessed as a scale of 1–5 (Edmonson *et al.* 1989). Parity and physiological status (pregnant or lactating) was obtained from farmer recall. All measures were recorded every 3 months after the second household visit, and dates were recorded (November 2015 to October 2016). Intervals coincided with the usual beginning/end of each of the following four subseasons in Nandi region: short rains (SR), November to January; hot dry (HD), February to April; long rains (LR), May to July; and cold dry (CD), August to October. Each season was assumed to be of equal duration (i.e. 92 days).

Milk production and composition

Daily milk production was measured on an individual basis by farmers using a Mazzican graduated milk urn (http://www.mazzican.com/, verified on 23 April 2017, Ashut Engineers Ltd, Nairobi, Kenya) and recorded in an exercise book for the duration of the study. Milk samples were collected in every season, bulked by household, then analysed for butterfat (%BF) (Gerber method) and milk density (kg/L at 20°C; Van Marle-Köster *et al.* 2000), with the analysis undertaken by New Kenya Co-operative Creameries, Kapsabet, Kenya. Milk solid non-fat (SNF) was calculated from %BF and density, using Richmond's formula (Bector and Sharma 1980), as follows:

$$\mathrm{SNF}(\%) = \left(\frac{\text{milk density(kg/L)}}{4}\right) + (0.22 * \mathrm{BF}(\%)) + 0.72. \tag{1}$$

Milk energy content (ECM) was calculated from the following equation by Tyrrell and Reid (1965):

$$\begin{aligned}\mathrm{ECM(MJ/kg)} &= 0.0386\mathrm{BF(g/kg\ milk)} \\ &+0.0205\mathrm{SNF(g/kg\ milk)} - 0.236.\end{aligned} \tag{2}$$

Locomotion data

Distance covered during daytime grazing was determined by using GPS-collar recorders (Waghorn 2008) fitted to an animal for two consecutive days (November–December 2016). Twelve animals, in total, were recorded over the three AEZs, namely LH1 (5), LH2 (3) and UM (4), with selection being based on diversity of grazing practices. Distance travelled was deemed to be the mean distance covered by animals measured in each AEZ.

Pasture and fodder yield estimation

Farm size, and identification of fields and crops planted in each field was conducted twice over the study period (November 2015, June 2016). Information on farm boundaries was provided by the farmers and the areas of individual farms and fields were determined using a laser range finder (Truth Laser Range Finder, Bushnell Outdoor Products, Kansas City, MO, USA) and the use of the plots were recorded. Samples of forages and fodder crops identified during these visits were collected, fresh weights were recorded using a digital scale (T28 scale, @weigh scales, Melbourne, Vic., Australia), and samples were then oven-dried (50°C, 3–5 days), ground through a 1 mm screen (IKA Handheld analytical mill; Cole-Parmer Scientific Experts, St Neots, Cambridgeshire, UK) and stored at room temperature in sealed plastic containers until analysed.

Pasture yield was estimated by placing exclusion cages (n = 36; 0.5 m H × 0.5 m L × 0.5 m W) at the study sites, one per village per season, and extrapolating the yield to area recorded as being under pasture. Grass was harvested at 3-month intervals by removing the biomass above 2.5 cm, which was then weighed, dried and ground as above. Biomass of Napier grass availability was estimated by multiplying the area under cultivation with published yield estimates (6.84 t/ha; Van Man and Wiktorsson 2003). Where Rhodes grass was grown as a crop, biomass was estimated using the yield index of Muyekho *et al.* (2003) (3.66 t/ha). Maize Stover biomass was estimated by applying farmer recall of grain yield, assuming a harvest index of 0.41 (Gerber *et al.* 2011). Sugarcane-top biomass was estimated by multiplying area under cultivation by the yield (39 t/ha) and assuming 4.89% as the leaf yield of the crop (Blignaut *et al.* 2005). Banana pseudo-stems in the diet were estimated from farmer recall.

Nutrient analysis for feed-digestibility determination

Nutrient analysis of feed was performed by wet chemistry for DM (AOAC Method 930.15), total N (AOAC Method 990.03), organic matter, neutral detergent fibre and acid detergent fibre (ADF; AOAC Method 973.18; Thornton and Herrero 2010). DMD was estimated using the following equation of Oddy *et al.* (1983):

$$\begin{aligned}\mathrm{DMD(g/100\ g\ DM)} &= 83.58 - 0.824 * \mathrm{ADF(g/100\ g\ DM)} \\ &+ (2.626 * \mathrm{N(g/100\ g\ DM)})\end{aligned} \tag{3}$$

Metabolisable energy-requirement (MER) estimation

Energy expenditure was calculated using equations from Goopy *et al.* (2018), which, in turn, were derived from equations published in 'Nutrient Requirements of Domestic Ruminants' (Touchberry and Lush 1950). Animal data were analysed by group based on age and sex; females (>2 years), males (>2 years), heifers (1–2 years), young males (1–2 years) and calves (<1 year). $\mathrm{MER_M}$ was estimated as follows:

$$\begin{aligned}\mathrm{MER_M(MJ/day)} &= (\mathrm{K} * \mathrm{S} * \mathrm{M}(0.26 * \mathrm{MLW}^{0.75}) \\ &*(\exp(-0.03\mathrm{A})))/((0.02 * \mathrm{M/D}) + 0.5)\end{aligned} \tag{4}$$

where K = 1.3 (the intermediate value for *Bos taurus* and *Bos indicus*), S = 1 for females and 1.15 for males, M = 1, MLW = mean liveweight for each season calculated via Eqn 5, as follows:

$$\mathrm{MLW(kg)} = \frac{\text{start LW(Kg) of a seaon + end LW(kg) of the season}}{2} \tag{5}$$

where A = age in years and M/D = metabolisable-energy content (ME MJ/DM kg). M/D was calculated via Eqn (6), as follows:

$$\mathrm{M/D} = 0.172\mathrm{DMD} - 1.707 \tag{6}$$

where DMD = % DM digestibility of feed.

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

$$\begin{aligned}&\mathrm{MER_G(MJ/day)} = \\ &(\mathrm{ADWG(kg)} * 0.92 * \mathrm{EC(MJ/kg)})/(0.043 * \mathrm{M/D})\end{aligned} \tag{7}$$

$$\mathrm{MER_L(MJ/day)} = (\mathrm{ADWL(kg)} * 0.92 * \mathrm{EC(MJ/kg)})/0.8 \tag{8}$$

where ADWG or ADWL (kg) = 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.

Daily milk consumption of pre-ruminant calves in litres (DCMC) was estimated using average LW plus the average daily LW gain (LWG) of calves between 0 and 3.5 months by using the equation of Radostits and Bell (1970), as follows:

$$\mathrm{DCMC(L)} = (\mathrm{LW(Kg)} * 0.107\mathrm{L/kg}) + \left(\frac{0.154\mathrm{L}}{0.1\mathrm{LWG(kg)}}\right) \tag{9}$$

The MER_L was calculated by calculating the daily milk yield (MY), as follows:

$$\mathrm{MY(L)} = \frac{\text{Total milk recorded per season(L)}}{\text{Number of days in season(L)}} + \mathrm{DCMC(L)} \tag{10}$$

MER_L was calculated as

$$\mathrm{MER_L(MJ/day)} = [(\mathrm{MY(L)} * \mathrm{ECM(MJ/kg)})/((0.02 * \mathrm{M/D}) + 0.4)] \tag{11}$$

Energy expended for locomotion was estimated as follows:

$$\mathrm{MER_T(MJ/day)} = \mathrm{DIST(km)} * \mathrm{MLW(kg)} * 0.0026\mathrm{(MJ)} \tag{12}$$

where DIST = average distance covered (km), MLW = mean LW as calculated in Eqn 6, 0.0026 MJ is the energy expended per kg LW (MJ/LW kg).

The daily total energy expenditure (MER_{Total}) for each animal category in each AEZ and season was then calculated as

$$\mathrm{MER_{TOTAL}(MJ/day)} = \mathrm{MER_M} + \mathrm{MER_{G/L}} + \mathrm{MER_L} + \mathrm{MER_T(females)} \tag{13}$$

$$\mathrm{MER_{TOTAL}(MJ/day)} = \mathrm{MERM} + \mathrm{MER_{G/L+}}\mathrm{MER_T} \text{ (males, heifers and young males)} \tag{14}$$

$$\mathrm{MER(MJ/day)_{TOTAL}} = \mathrm{MER_M} + \mathrm{MER_{G/L}(calves)} \tag{15}$$

Daily CH_4 production (DMP) and EF calculation

DMI was calculated as follows:

$$\mathrm{DMI(kg)} = \mathrm{MER_{Total}(MJ/day)}/(\mathrm{GE(MJ/Kg)} * (\mathrm{DMD}/100))/0.81 \tag{16}$$

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

$$\mathrm{DMP(g)} = 20.7 * \mathrm{DMI(Kg/day)} \tag{17}$$

Mean DMP for each class of animal in each seasons was calculated. In the following, this was used to calculate an

Table 1. Cattle population by category (females >2 years, males >2 years, heifers 1–2 years, young males 1–2 years and calves <1 year), sales, purchases, deaths, births and loans over the four subseasons (short rains, hot dry, long rains and cold dry) for the three agro-ecological zones (AEZs: lower highland 1, lower highland 2 and upper midlands) of Nandi County, Kenya

The total number of animals used in the emission calculations comprised growing animals being used to derive emissions in different cattle categories

AEZ	Cattle category	Season				Management					
		Short rains	Hot dry	Long rains	Cold dry	Sale	Purchase	Death	Birth	Loan	Calf to young adult
Lower highland 1	Females	291	287	280	267	51	31	4	–	0	–
	Males	8	7	4	4	5	1	0	–	0	–
	Heifers	95	115	136	139	34	20	0	–	1	58
	Young males	33	36	37	46	24	9	0	–	0	28
	Calves	143	139	152	150	23	6	3	110	1	–
Lower highland 2	Females	92	89	84	80	17	7	2	–	0	–
	Males	12	10	10	9	5	2	0	–	0	–
	Heifers	23	26	31	36	3	5	0	–	1	12
	Young males	11	11	9	7	10	0	0	–	0	6
	Calves	46	51	60	62	11	0	3	47	0	–
Upper midlands	Females	66	61	59	55	12	5	3	–	1	–
	Males	19	15	15	14	7	2	0	–	3	–
	Heifers	12	14	19	25	2	3	0	–	0	12
	Young males	0	2	7	13	0	4	0	–	0	8
	Calves	30	28	24	24	2	1	1	15	0	–
Total Nandi	Females	449	437	423	402	80	43	9	–	1	–
	Males	39	32	29	27	12	5	0	–	3	–
	Heifers	130	155	186	200	39	28	0	–	2	82
	Young males	44	49	53	66	34	13	0	–	0	42
	Calves	219	218	236	236	33	7	7	172	2	–

annual zenteric methane EF (CH_4 kg/head.year. DMP for pre-ruminant calves (0–3.5 months) was excluded from EF calculations for calves on the assumption that calves at this age produce negligible emissions (Reed *et al.* 1990).

$$\mathrm{EF}\left(\frac{\mathrm{CH_4}\frac{\mathrm{kg}}{\mathrm{head}}}{\mathrm{y}}\right)=\frac{\left(\mathrm{DMP_{Short\,rains}}+\mathrm{DMP_{Hot\,dry}}+\mathrm{DMP_{Long\,rains}}+\mathrm{DMP_{Cold\,dry}}\right)*365}{4*1000} \tag{18}$$

Statistical analyses

Descriptive statistics (mean, standard error of means (s.e.m.)) were calculated for milk yield, 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, and milk production.

Results

Cattle were grouped in five classes on the basis of age and sex (Table 1). Populations varied among AEZ, with the largest numbers of female cattle being observed in LH1, followed by LH2 and UM. The pattern was independent of individual seasons; nonetheless, numbers declined due to sales. In contrast, the numbers of heifers and young males (87 calves were reclassified to heifers and 44 calves to young males) during the study period. Many females (40.3%) calved, while mortality in females and calves was 2% and 7.5% respectively.

LH1 had the highest LW for females, heifers, young males and calves; LH2 had the highest LW for males and UM recorded the lowest LW among the three zones (Table 2).

Cattle of all categories showed diminished LW gain during the HD season, while the highest mean weight flux was seen during the SR season (Fig. 1).

Mean daily milk production differed between LH1 and UM (5.4 vs 3.7 L; $P = 0.003$), but the box and whisker plot (Fig. 2) indicated that this difference was likely to be due to several outlying, high-yielding cows in LH1 rather than a widespread higher production. Average daily distances covered when grazing were lowest in LH1 (4.9 km), highest in LH2 (11 km) and intermediate in UM (8.5 km).

Milk energy content (ECM) did not differ among seasons (SR: 3.2 ± 0.02; HD: 3.2 ± 0.04; LR: 3.2 ± 0.03; CD: 3.1 ± 0.03 MJ/L; $P = 0.50$) but differed among AEZs (LH1: 3.1 ± 0.04; LH2: 3.2 ± 0.05; UM: 3.5 ± 0.07 MJ/L; $P = 0.03$).

Weighted mean DMD of the feed basket varied among seasons and AEZs, but it was in a fairly narrow range of 60.0–68.4% (Table 3). Maize stover and sugarcane tops were the most common crop residues. Maize stover was available only in SR and HD seasons and sugarcane tops common in the UM zone only.

Table 2. Seasonal (short rains, hot dry, long rains and cold dry) mean liveweight (kg) ± s.e.m. for females and males (>2 years) heifers and young males (1–2 years) and calves (<1 year) for the three agro-ecological zones (AEZ: lower highland 1, lower highland 2, upper midlands) of Nandi County, Kenya

AEZ	Short rains	Hot dry	Long rains	Cold dry
		Females (>2 years)		
Lower highland 1	323.7 ± 3.64	327.5 ± 4.08	318.7 ± 3.91	320.0 ± 3.94
Lower highland 2	284.6 ± 6.58	288.4 ± 6.76	284.1 ± 7.08	291.7 ± 7.35
Upper midlands	251.7 ± 7.31	258.4 ± 8.00	262.4 ± 8.27	271.2 ± 8.14
Mean	305.1 ± 3.42	309.9 ± 3.69	304.3 ± 3.56	308.1 ± 3.47
		Males (>2 years)		
Lower highland 1	251.4 ± 32.74	238.8 ± 23.48	282.1 ± 15.74	289.9 ± 15.63
Lower highland 2	299.6 ± 25.15	309.9 ± 24.17	300.6 ± 18.67	326.2 ± 20.87
Upper midlands	225.5 ± 12.87	225.4 ± 13.24	243.0 ± 12.89	260.6 ± 14.20
Mean	253.6 ± 15.92	254.8 ± 14.36	268.3 ± 12.37	286.8 ± 15.17
		Heifers (1–2 years)		
Lower highland 1	188.0 ± 5.93	195.1 ± 5.86	195.1 ± 5.91	202.7 ± 6.61
Lower highland 2	156.8 ± 11.77	170.1 ± 12.06	172.3 ± 11.10	181.0 ± 9.15
Upper midlands	140.7 ± 16.58	144.8 ± 16.75	158.5 ± 13.78	161.5 ± 13.79
Mean	178.3 ± 5.57	186.6 ± 5.47	188.1 ± 5.49	194.2 ± 5.71
		Young males (1–2 years)		
Lower highland 1	156.6 ± 9.23	165.2 ± 9.32	169.7 ± 9.76	158.6 ± 3.10
Lower highland 2	128.7 ± 12.13	150.1 ± 11.93	153.4 ± 8.88	165.8 ± 10.00
Upper midlands	–	112.6 ± 5.40	118.4 ± 9.70	143.3 ± 10.53
Mean	149.6 ± 9.34	159.7 ± 8.39	161.8 ± 8.53	156.4 ± 7.47
		Calves (<1 year)		
Lower highland 1	70.7 ± 2.40	73.2 ± 2.55	70.6 ± 2.69	66.4 ± 2.54
Lower highland 2	64.7 ± 4.42	61.5 ± 3.78	58.6 ± 4.19	60.3 ± 4.60
Upper midlands	58.8 ± 4.45	70.4 ± 6.04	63.8 ± 6.58	70.6 ± 8.53
Mean	67.7 ± 1.94	69.7 ± 2.05	66.3 ± 2.09	64.7 ± 2.12

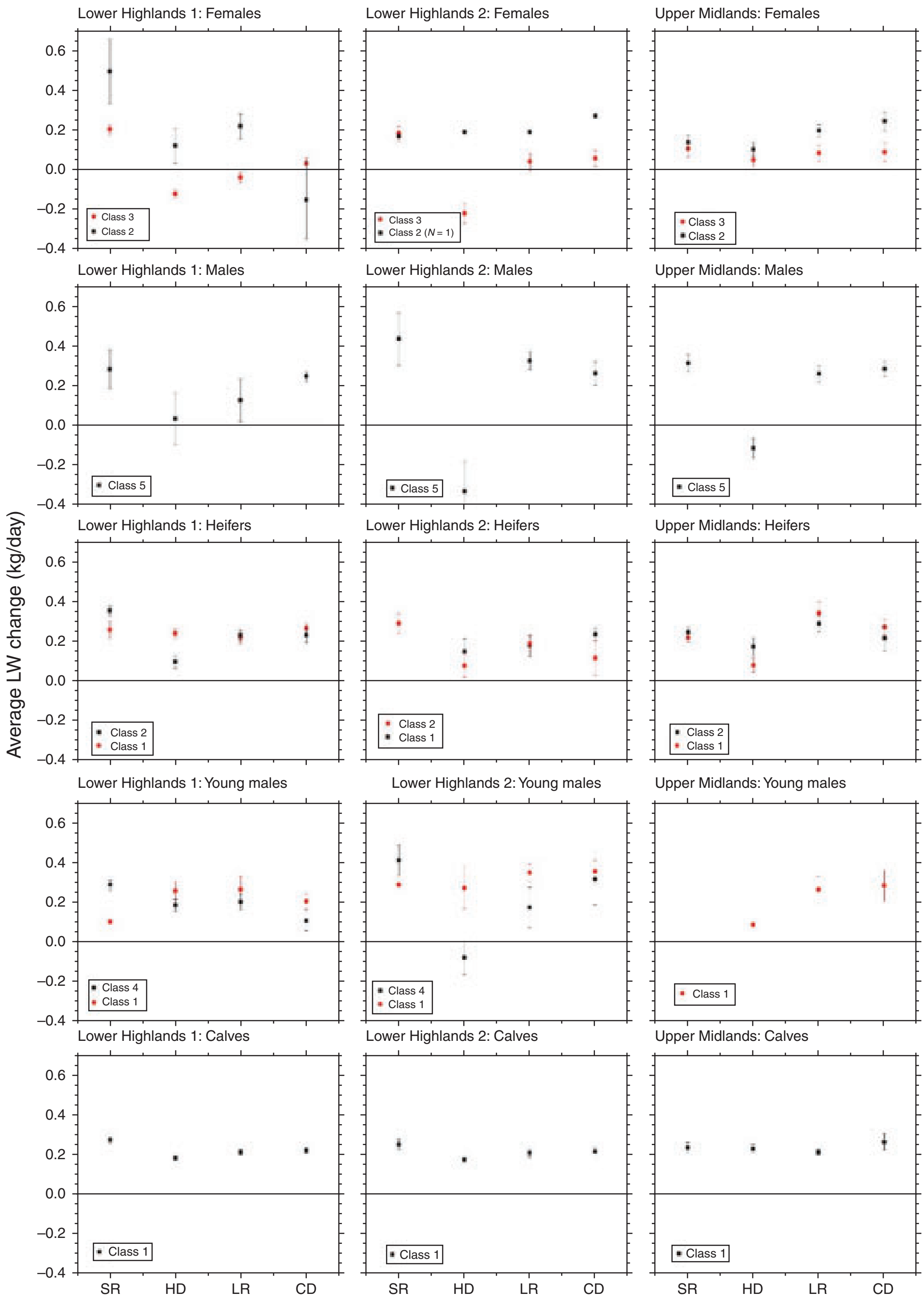

Fig. 1. Seasonal mean weight changes (kg/day) of females (>2 years; Class 3 and Class 2) and males (>2 years; Class 5), heifers (1–2 years; Class 2 and Class 1), young males (1–2 years; Class 4 and Class 1) and calves (<1 year; Class 1). Class 2 in the female category represents those females that are non-productive, while Class 1 in the heifer category represents the young heifers that had just turned >1 year during the study period. Class 1 in the young male category represents the young males that had just turned >1 year during the study period. SR, short rains; HD, hot and dry; LR, long rains; CD, cold and dry.

Total MER and MER constituents are given for females (>2 years; Table 4). The total MER and MER constituents for males (>2 years), heifers (1–2 years), young males (1–2 years) and calves (0–1 years) are shown in Tables S1–S4, available as Supplementary material to this paper. MER_M was the largest component of MER for all classes of cattle across all seasons and AEZs except for female >2-year cattle class, for which the MER_L was the largest component. The major source of the variability in MER among seasons was $MER_{G/L}$.

On the basis of these and DMD data (Table 3), the DMP rate (Table S5, available as Supplementary material to this paper) and, thus, annual EFs for all classes of cattle in each AEZ were calculated (Table 5). There was a difference in EF among cattle categories (P = 0.0003), but no EF difference was evident among AEZs (P = 0.14).

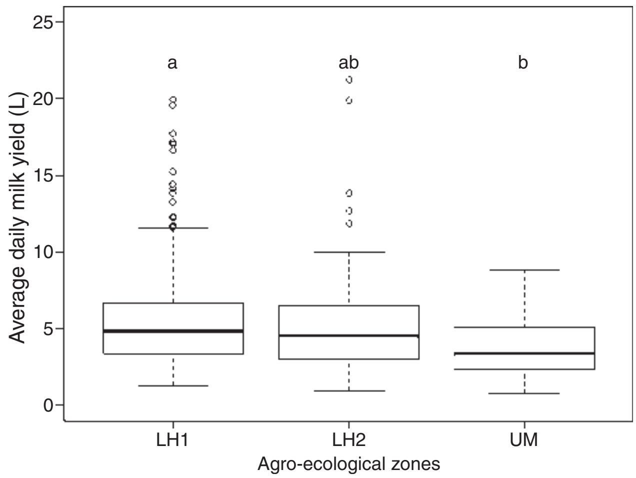

Fig. 2. Box and whisker plot of mean daily milk production for lower highland 1 (LH1), lower highland 2 (LH2) and upper midlands (UM). The thick line denotes mean daily milk production, while the box denotes values between 1st and 3rd quartiles. The whiskers show the 95% confidence interval and the circles show the outliers. Differences among agro-ecological zones (AEZs) (P < 0.05) are denoted by different letters.

Discussion

Methane emissions of cattle in LH2 were generally the highest of the AEZs for all categories, although differences among zones within classes were not large. This was despite animals in LH1 generally being heavier. With LW being a key determinant of MER_M (Touchberry and Lush 1950), enteric CH_4 being positively correlated with feed intake (Molano and Clark 2008) and voluntary intake being positively correlated with LW (Robinson and Oddy 2016), it would be expected that differences in calculated EF would align with observed LW differences across the AEZs. That this was not so can probably be attributed to a combination of the observed differences among zones in LW flux and locomotion, plus small differences among zones in average DMD, along with the assumption that CH_4 yield is a constant fraction of DM in forages, unrelated to digestibility. Feed availability is a major constraint in smallholder livestock production systems of Kenya, especially in the dry season(s), a situation exacerbated by a tendency to keep more livestock than can be adequately fed (Hang *et al.* 2011). The present study showed a clear seasonal effect of feed restriction through the observed LW losses in productive females and reduced gains in other classes of cattle (Fig. 1), (mainly) during the HD season. This effectively resulted in a lower DMP, as in some cases cattle mobilised endogenous tissue to meet energy requirements, rather than meeting them through consumption (and fermentation) of feed. Feed availability may also influence distances covered for grazing and watering, thus affecting energy expenditure.

Table 3. Composition of seasonal (short rains, hot dry, long rains and cold dry) diets and their dry-matter digestibility (DMD) in the three agro-ecological zones (lower highland 1, lower highland 2 and upper midlands) in Nandi County, Kenya

n.a., not available during that season

Agro-ecological zone	Feedstuff	Short rains		Hot dry		Long rains		Cold dry	
		Proportion (%)	DMD (%)	Proportion (%)	DMD (%)	Proportion (%)	DMD (%)	Proportion (%)	DMD (%)
Lower highland 1	Pasture	68.2	64.9	68.2	64.9	80.7	66.7	81.0	70.1
	Napier	13.1	62.7	13.1	62.7	16.2	62.7	15.9	62.7
	Rhodes grass	2.5	53.1	2.5	53.1	3.1	53.1	3.1	53.1
	Maize stover	16.2	59.3	16.2	59.3	n.a.	–	n.a.	–
	Average DMD		63.4		63.4		65.6		68.4
Lower highland 2	Pasture	54.7	59.2	54.7	59.2	79.8	64.8	80.1	66.0
	Napier	12.1	67.9	12.1	67.9	16.3	67.9	16.1	67.9
	Rhodes grass	2.1	53.1	2.1	53.1	2.9	53.1	2.8	53.1
	Maize stover	30.1	59.3	30.1	59.3	n.a.	–	n.a.	–
	Banana pseudo stems	1.0	69.6	1.0	69.6	1.0	69.6	1.0	69.6
	Average DMD		60.3		60.3		65.1		66.0
Upper midlands	Pasture	55.1	69.4	55.1	69.4	56.4	62.3	53.0	63.4
	Napier	8.3	61.2	8.3	61.2	11.1	61.2	11.9	61.2
	Rhodes grass	0.2	53.1	0.2	53.1	0.2	53.1	0.2	53.1
	Maize stover	11.8	59.3	11.8	59.3	n.a.	–	n.a.	–
	Banana pseudo stems	1.0	69.6	1.0	69.6	1.0	69.6	1.0	69.6
	Sugarcane tops	23.6	55.3	23.6	55.3	31.4	55.3	33.8	55.3
	Average DMD		64.2		64.2		60.0		60.4

Table 4. Seasonal (short rains, hot dry, long rains and cold dry) 1st quartiles, mean and 3rd quartiles for metabolisable-energy requirements (MER, MJ/day) for maintenance (MER_M), weight gain/loss ($MER_{G/L}$), lactation (MER_L), locomotion (MER_T) and total MER of females (>2 years) in lower highland 1, lower highland 2 and upper midlands of Nandi County, Kenya

Parameter	Short rains (MJ/day)					Hot dry (MJ/day)					Long rains (MJ/day)					Cold dry (MJ/day)				
	MER_M	$MER_{G/L}$	MER_L	MER_T	Total MER	MER_M	$MER_{G/L}$	MER_L	MER_T	Total MER	MER_M	$MER_{G/L}$	MER_L	MER_T	Total MER	MER_M	$MER_{G/L}$	MER_L	MER_T	Total MER
Lower highland 1																				
1st quartile	28.83	–0.59	20.86	3.6	44.62	29.08	–5.92	16.99	3.5	39.52	28.02	–4.55	17.15	3.4	42.05	27.97	–3.62	17.08	3.5	43.38
Mean	32.15	9.71	41.91	4.1	70.33	32.51	–1.12	35.12	4.2	57.03	31.62	1.61	37.74	4.1	62.16	31.34	3.76	38.00	4.1	64.19
3rd quartile	35.10	17.25	64.24	4.6	88.29	35.45	4.62	39.18	4.6	65.93	35.12	7.95	49.27	4.5	71.84	34.25	12.39	48.95	4.6	77.31
Lower highland 2																				
1st quartile	26.17	–0.28	18.20	7.1	39.98	26.37	–9.72	11.86	6.9	37.07	24.69	–3.11	16.19	6.7	40.61	25.63	–2.37	16.77	7	45.57
Mean	29.04	7.90	53.35	8.1	70.98	29.84	–2.99	38.85	8.2	60.31	28.87	4.36	38.28	8.1	64.69	29.30	3.93	44.87	8.3	71.61
3rd quartile	32.36	13.15	80.12	9.4	80.40	33.24	2.27	62.87	9.3	64.96	32.29	11.12	45.84	9.3	77.21	32.43	10.76	74.11	9.5	81.79
Upper midlands																				
1st quartile	22.95	–1.24	21.77	5.2	33.27	23.31	–2.10	9.91	5.2	33.88	24.16	0.00	9.49	5.2	35.38	24.36	–1.17	10.77	5.6	41.01
Mean	26.36	5.96	41.89	6.5	57.03	26.81	3.28	24.83	6.6	49.01	27.72	4.92	31.20	6.7	57.83	28.45	6.64	33.71	7	62.55
3rd quartile	30.19	11.03	60.88	7.7	78.92	30.83	8.12	32.78	7.7	61.08	31.36	6.73	40.82	8.1	73.74	32.36	13.64	42.28	8.6	78.23
Total Nandi																				
1st quartile	27.16	–0.57	20.37	3.8	40.34	27.26	–5.87	15.13	3.8	37.77	26.73	–3.92	16.16	3.8	39.57	26.95	–3.28	16.35	3.8	43.38
Mean	30.65	8.79	43.89	5.3	68.36	31.16	–0.86	34.71	5.3	56.57	30.52	2.78	37.02	5.2	62.05	30.53	4.19	38.86	5.3	65.46
3rd quartile	33.99	15.98	66.87	6.4	84.62	34.36	4.73	38.83	6.6	65.50	33.71	10.17	46.32	6.4	73.18	33.74	12.20	52.05	6.5	78.08

Table 5. Emission factors (mean ± s.e.m., kg methane (CH_4)/head.year) for females and males (>2 years) heifers and young males (1–2 years) and calves (<1 year) in the three agro-ecological zones (lower highland 1, lower highland 2, upper midlands) of Nandi County, Kenya

Values followed by the same letter are not significantly different (at $P = 0.05$)

Agro-ecological zone	Emission factors (kg CH_4/head.year)				
	Females (>2 years)	Males (>2 years)	Heifers (1–2 years)	Young males (1–2 years)	Calves (<1 year)
Lower highland 1	50.2 ± 1.41f	41.4 ± 3.26f	28.7 ± 0.94g	32.6 ± 1.38h	29.4 ± 1.02i
Lower highland 2	54.8 ± 3.32f	51.4 ± 3.49f	27.9 ± 1.84g	34.5 ± 2.69h	28.5 ± 2.01i
Upper midlands	46.5 ± 2.87f	43.0 ± 2.33f	27.8 ± 2.30g	24.8 ± 2.98h[A]	28.1 ± 2.75i
Total Nandi	50.6 ± 3.34a	45.5 ± 5.12b	28.5 ± 2.18c	33.2 ± 3.42d	29.0 ± 2.41e

[A]There were no young males in the upper midlands zone during the short rains; thus, the emission factor was calculated by multiplying the daily CH_4 production (DMP) by 274 days (3 seasons) instead of 365 days (4 seasons).

There were large differences between AEZs in the mean distance travelled for locomotion during grazing, but another consideration is that (due to resource constraints) all locomotion measurements were taken during HD season, when distances travelled might have been expected to be the greatest. Thus, it may be posited that MER for locomotion (MER_T expenditure) may have been overestimated for the other seasons.

Lactation is an energy-demanding function of dairy cattle. Cattle with high milk production have high feed intakes (van Zijderveld *et al.* 2011). The level of milk production directly affects EF calculations as increases in feed intake lead to higher rates of enteric fermentation. In the present study, LH1 showed the highest milk production as well as having the heaviest females. MY from cows in all zones in the present study (mean: 1866 L/head.year) was higher than the IPCC (Tier I) estimate of 475 L/head.year. There was a difference evident among AEZs in milk production, which supports the idea that livestock kept in a given area are a function of AEZ because it influences the feed base and, thus, potential productivity (Bebe 2003). Thus, it can be anticipated that enteric CH_4 emissions will tend to increase with rising levels of production. The present study also demonstrated that milk composition could affect EFs. The calculated energy content of milk in the present study was greater than the default value adopted by Goopy *et al.* (2018) (3.2 vs 3.05 MJ/kg). This suggests that the calculated EFs for the earlier study might have been underestimated for females >2 years, although the quantum of such underestimation is likely to be minor, given both the relatively minor differences in ECM and the small contribution of milk production to total MER in the Nyando study.

The (weighted mean) DMD of feed basket in the present study was greater than were the IPCC default estimates (of 50–55%) for African forages (Dong *et al.* 2006). Differences in DMD among AEZs, with mean values varying in a range of 60–68.4% (Table 3), are likely to have influenced estimates of DMP and, thereby, EFs. The observed variability in DMD among AEZs agrees generally with the work of Lee *et al.* (2017) regarding variability in nutritive value of forage grasses across bioclimatic zones. The DMD of feed baskets in the present study was 10–15% higher than that assigned to Africa for Tier I estimates and this can be considered a significant point of difference in the calculation of EFs, but our calculated EFs were still lower than Tier I estimates for males and growing stock, with those for mature females being only slightly higher, despite these animals being over 50% heavier than the IPCC Tier I 'typical animal'.

Livestock systems in the current study area (Nandi) and Nyando (Gordon and Illius 1994) may be considered generally comparable in relation to their geography and climatic conditions. However, the systems in the Nandi area were demonstrated to feature animals of greater LW and higher milk production than those in Nyando, which may be attributable to climatic conditions favouring production of better feed, superior animal husbandry or a combination of both. However, determining causality of these observed differences was outside the scope of the present study. A comparison of EFs from IPCC Tier I estimates (for unspecified African cattle), the Nyando study (Gordon and Illius 1994) and results from the current study is given below (Table 6). The EFs for all categories of cattle showed some divergence from Tier I estimates, but key parameters varied in ways that make comparison among the three groups of measurements challenging.

For example, females in the Nyando study had LWs similar to the IPCC estimates, but much lower EFs; this was attributed in part to observed seasonal LW losses that were also observed in the present study. Mature females in Nandi were heavier and had a greater milk production (both in comparison to the Nyando study and IPCC estimates), which led to higher EFs than IPCC default estimates. One consistent point of difference between IPCC estimates and those of both Nyando and Nandi is the average digestibility of the feed baskets in both areas, which was 5–15% higher than that of the assumed poor-quality diets attributed to African cattle by IPCC. Again, in Nandi (but not Nyando) daily milk production and calf growth rates were considerably greater than is assumed in the IPCC TIER I estimate for African cattle. These differences demonstrated clearly that current assumptions regarding LW, animal growth, lactation yield and the 'typical' feed basket, are unreliable and need to be reviewed.

Although several changes to improve the precision of measurement were made in the study, including better scheduling of LW measurement and the assessment of milk energy composition, in many respects, the present study was limited by the same factors as the Nyando study (Goopy *et al.* 2018). The energy value of tissue is highly variable, depending on its

Table 6. A comparison between Intergovernmental Panel on Climate Change (IPCC) default values and observed values from Nyando (Goopy *et al.* 2018) and Nandi provinces, Kenya, for mean liveweight (LW, kg) and enteric methane emission factors (EFs, kg CH_4/head.year) for different classes of cattle: female (>2 years), males (>2 years), heifers (1–2 years), young males (1–2 years) and calves (<1 year)

Cattle category	IPCC (2006) Tier I		Nyando study		Present study	
	Mean LW (kg)	EF	Mean LW (kg)	EF	Mean LW (kg)	EF
Females (>2 years)	200	41	216.3	28.3	306.9	50.6
Heifers (1–2 years)	–	31	154.6	23.0	186.8	28.5
Males (>2 years)	275	49	216.0	35.9	265.9	45.5
Young males (1–2 years)	–	31	143.5	30.1	156.9	33.2
Calves (<1 year)	75	16	73.4	17.3	73.3	29.0

composition, and lack of knowledge of the nature of tissue deposition (or loss) in animals introduces an error of unknown magnitude. Because LW changes are quantitatively of lesser influence (than maintenance or, for females, lactation) on total MER of smallholder cattle, it is less likely that this is of key importance. Additionally, measurement of locomotion of more induvial cattle over several seasons may improve precision, but at a significant cost in resources. It needs to be acknowledged that even the limited measurements undertaken here are a substantial improvement over the allocation of a fixed increment of maintenance energy, as is used in deriving TIER I estimates.

The present study also highlighted the heterogeneity present in ostensibly similar production systems. More consideration needs to be given to identifying and quantifying the sources of this variability in attempting to develop regional, let alone countrywide, specific EFs. Improved TIER II EFs have been produced for livestock in developing economies, some being in Africa (Tran *et al.* 2011; Lesosky *et al.* 2012; Du Toit *et al.* 2014). However, often these studies will refer to derivative literature, other records whose accuracy has not been critically assessed or simply apply IPCC default values when data for a particular class of information are lacking. This presents a potential limitation to the precision, and, ultimately, utility of such studies,

Conclusions

The present study is the second on ruminant CH_4 emissions from smallholder livestock systems in the highlands of Kenya. The reliance of the present approach on measurement of important aspects of animal metabolism directly related to energy requirement, feed intake and, ultimately, CH_4 production, emphasises both the inherent robustness of the approach and the heterogeneity in ostensibly equivalent systems. This suggests that (1) IPCC Tier 1 approach tends to over- and underestimate emissions from smallholder systems and (2) studies that rely partly (or heavily) on TIER I default values for their calculations may be limited in their utility. The current findings indicate overwhelmingly that estimates based on measurement, rather assumption, are required if valid enteric emissions estimates are desired.

Conflicts of interest

The authors declare no conflicts of interest.

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