Agricultural Systems 161 (2018) 72–80

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – Results for Nyando, Western Kenya

J.P. Goopy[a,c,*], A.A. Onyango[a,b], U. Dickhoefer[b], K. Butterbach-Bahl[a,d]

[a] Mazingira Centre, International Livestock Research Institute, Nairobi, Kenya
[b] University of Hohenheim, Stuttgart, Germany
[c] University of Melbourne, Victoria, Australia
[d] Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research, Atmospheric Environmental Research, Garmisch-Partenkirchen, Germany

ARTICLE INFO

Keywords:
Enteric methane
Ruminant
Cattle
GHG inventory
East Africa

ABSTRACT

In Africa, the agricultural sector is the largest sector of the domestic economy, and livestock, are a crucial component of agriculture, accounting for ~45% of the Kenyan agricultural GDP and > 70% of African agricultural greenhouse gas (GHG) emissions. Accurate estimates of GHG emissions from livestock are required for inventory purposes and to assess the efficacy of mitigation measures, but most estimates rely on TIER I (default) IPCC protocols with major uncertainties coming from the IPCC methodology itself. Tier II estimates represent a significant improvement over the default methodology, however in less developed economies the required information is lacking or of uncertain reliability. In this study we developed an alternative methodology based on animal energy requirements derived from field measurements of live weight, live weight change, milk production and locomotion to estimate intake. Using on-farm data, we analysed feed samples to produce estimates of digestibility by season and region, then and used these data to estimate daily methane production by season, area and class of animal to produce new emission factors (EF) for annual enteric CH_4 production. Mean Dry Matter Digestibility of the feed basket was in the range of 58–64%, depending on region and season (around 10% greater than TIER I estimates). EFs were substantially lower for adolescent and adult male (30.1, 35.9 versus 49 kg CH_4) and for adolescent and adult female (23.0, 28.3 versus 41 kg), but not calves (15.7 versus 16 kg) than those given for "other" African cattle in IPCC (Tier I) estimates. It is stressed that this study is the first of its kind for Sub-Sharan Africa relying on animal measurements, but should not automatically be extrapolated outside of its geographic range. It does however, point out the need for further measurements, and highlights the value of using a robust methodology which does not rely on the (often invalid) assumption of *ad libitum* intake in systems where intake is known or likely to be restricted.

1. Introduction

In Africa, the agricultural sector is the largest sector of the domestic economy, employing between 70% and 90% of the total labour force (AGRA, 2017).

Livestock, whether based on pastoralism or as part of mixed cropping/livestock systems, are a crucial component of agriculture and it was estimated that livestock contributes to about 45% to the Kenyan agricultural gross domestic product (ICPALD, 2013). The impact of livestock on the environment in Africa is high and it is estimated that > 70% of African agricultural greenhouse gas (GHG) emissions are due to livestock production, dominated by CH_4 emissions from enteric fermentation (Tubiello et al., 2014; http://www.fao.org/faostat/en/#data/GT). Whilst an accurate picture of GHG emissions from livestock is required for inventory purposes, there is also a pressing need to ensure that estimates of livestock GHG emissions reflect the actual case both for national reporting and development and monitoring, reporting and verification (MRV) of nationally determined contributions (NDC) on mitigation of GHG emissions from the livestock sector (Bodansky et al., 2016).

There are extant studies which comprehensively model ruminant livestock emissions using a digestion and metabolism model (RUMINANT), spatially explicit data on livestock numbers and generalized assumptions on regional feed availability and digestibility (Herrero et al., 2008, 2013; Thornton and Herrero, 2010). Other studies (Tubiello et al., 2014) rely on TIER I IPCC protocols (Dong et al., 2006)

* Corresponding author at: Mazingira Centre, International Livestock Research Institute, Nairobi, Kenya.
E-mail address: j.goopy@cgiar.org (J.P. Goopy).

https://doi.org/10.1016/j.agsy.2017.12.004
Received 20 June 2017; Received in revised form 12 December 2017; Accepted 13 December 2017

with major uncertainties coming from the IPCC methodology itself. One area of uncertainty is the accuracy of livestock census data used to model animal population densities and overall emissions – currently (as at 2016) FAO use 2005 data for estimating cattle populations. This of course can be addressed by the provision of more current (and accurate) census data. A more problematic area of uncertainty is the representativeness of ruminant CH_4 emission factors (EF) themselves. TIER I estimates (the most basic level) use IPCC mandated values based on a variety of published literature that report measured ruminant CH_4 emissions scaled to a year as kg CH_4 per head – studies which have almost exclusively been carried out in ruminant production systems in advanced, Western countries. These estimates are then "adjusted" for developing economy systems, on the basis of expert opinion. To date, little empirical data has been presented to corroborate or challenge these estimates for African livestock systems.

Tier II estimates represent a significant improvement over the TIER I default methodology, as country specific livestock data (on e.g.: live weight (LW), feed and activity) are used to refine EFs. Recently completed studies in South Africa (Du Toit et al., 2013) and Benin (Kouazounde et al., 2015) have highlighted substantial discrepancies between TIER I and TIER II emission estimates in African livestock systems.

However, there are a number of issues that occur when directly applying TIER II methodology to African smallholder livestock systems. Tier II methodology relies on estimates of enteric CH_4 production based on feed intake and diet quality, with putative intake being derived from energy expenditure estimates. Energy expenditure in turn, is based on metabolic processes (maintenance, growth, lactation, locomotion). There are (at least) two significant issues with applying this model in the context of smallholder agriculture. Firstly, the premise of estimating intake based on diet quality is grounded in the assumption of unrestricted or *ad libitum* intake. In smallholder farms, animals are typically held in kraals or bomas overnight and this practice has been demonstrated to restrict voluntary intake (Nicholson, 1987; Ayantunde et al., 2008). Secondly, in estimating the Metabolizable Energy Requirement (MER) for growth, animals are assumed to grow at a steady, constant rate throughout the year. In practice ruminants on rain-fed tropical pasture will lose weight for part of the year due to feed shortage e.g. in dry seasons (Norman, 1965) and grow at higher than average rates for the balance in wet seasons with ample available feed. Because ruminants use mobilized body tissue with a higher efficiency than ingested feed (CSIRO, 2007), this has important implications for the estimation of intake throughout the year.

Considering the potential impact of the above on estimates of intake and thus enteric CH_4 emissions, we purposed to measure LW and seasonal LW flux as well as milk yield and locomotion of cattle and feed availability and its nutritional quality in a smallholder livestock system in the Nyando area of Western Kenya to allow us to provide better estimates of enteric CH_4 emissions of cattle in smallholder systems using a Tier II approach.

We hypothesized that considering seasonal changes in feed availability and nutritional quality as well as animal performance (i.e.: by the addition of in-situ measurements) would result in marked improvement in the accuracy of calculated livestock emissions as compared to the standard IPCC Tier 1 approach.

2. Materials and methods

2.1. Study area

The study area, a 10 by 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), was selected by the Climate Change Agriculture and Food Security (CCAFS) program of Consultative Group on International Agricultural Research (CGIAR) institutes, as a primary study site in the East African highlands (Fig. 1). The site is named Lower Nyando and has been described in detail by Verchot et al. (2008). Details on the sampling frame and region of study are available at: http://www.ccafs.cgiar.org/resources/baseline-surveys.

Briefly, a longitudinal survey was carried out in 60 households within a total of 20 villages located in the three dominant landscape positions (the Lowlands, the Slopes, and the Highlands). Proportional probability sampling based on the clusters yielded 24 farm(er)s in the Lowlands, 18 in the Slopes, and 18 in the Highlands to give a total sample of 60 households. The landscape positions were heterogeneous with regards to climate, soil type, vegetation, and livestock management, but mixed crop/livestock systems predominate. Climate is humid to sub-humid, with annual rainfall of 1200–1725 mm in a bi-modal pattern, allowing for two cropping seasons a year. There are four marked seasons classified as long dry season (January–March), long wet season (April–June), short dry season (July–September), and the short wet season (October–December) (Zhou et al., 2007).

Pastures in the Nyando region comprise mainly grasses such as *Digitaria gazensis*, *D. ciliaris*, *Eragrostis superba.*, *E. aspera Hyparrhenia collina*, *Cynodon dactylon*, *Cappillipedium parviflorum* and *Bracharia* spp. (Verchot et al., 2008). Pasture, both in smallholder farms and communal areas tends to be subject to continuous year-round grazing.

The cattle population comprised East African shorthorn zebus and numerous indeterminate zebu x *Bos taurus* crosses. Herd size ranged from 1 to 19 cattle per smallholding.

2.2. Animals and animal performance data

Data was collected at approximately three month intervals from July 2014 to July 2015, to approximately coincide with the four sub-seasons observed in the study area. All cattle in each selected smallholding were identified using individually numbered ear tags (Allflex Europe SA, Vitre) applied during the initial data collection visits. Farmers provided information on parity, pregnancy, and lactation status. Age was estimated from dentition (Torell et al., 1998), while LW was determined on-farm using a portable weighing scale fitted with LED display (Model EKW, Endeavor Instrument Africa Limited, Nairobi). Heart girth was measured at each LW recording, while body condition score was assessed on a 1 to 5 scale (Edmonson et al., 1989). Milk production was recorded by farmers who were supplied with a graduated plastic container (1500 ml Jug, Kenpoly Limited, Nairobi) and a notebook that was collected and collated every two months. Cattle were classified as calves (less than one year old), heifers/young males (1–2 years old), or cows/adult males (above 2 years old).

2.3. Feed resources – pasture and fodder yield determination

Farms were visited at the beginning of each of the two cropping seasons (Short Wet and Long Wet) to assess total farm and individual plot/field area, using a laser range finder (Truth Laser Range Finder, Bushnell Outdoor Products, USA) and land use (e.g.: crop, Napier grass, fallow).

Pasture yield was estimated using wire mesh enclosure cages (0.5 m × 0.5 m × 0.5 m) (Holechek et al., 1982) to exclude grazing (one per household per village). Every three months, coinciding with the middle of the different seasons, the pasture growth was harvested from each cage with scissors ~2.5 cm above the ground. Individual samples were placed in pre-weighed paper bags and weight recorded using a digital scale (Citizen Model CTG6H, Citizen Scale Inc., USA). The cage was replaced in the same position until the next sampling. Available pasture biomass was estimated for the sampled farms in each zone by season (t dry matter (DM)/ha) by extrapolating sample mass by area under pasture for each farm and aggregating areas for all farms in the survey, by zone.

Crop stover biomass available for fodder was determined from farmer recall of grain yield, then applying crop-specific harvest indexes for: maize (Hay and Gilbert, 2001), sorghum (Prihar and Stewart,

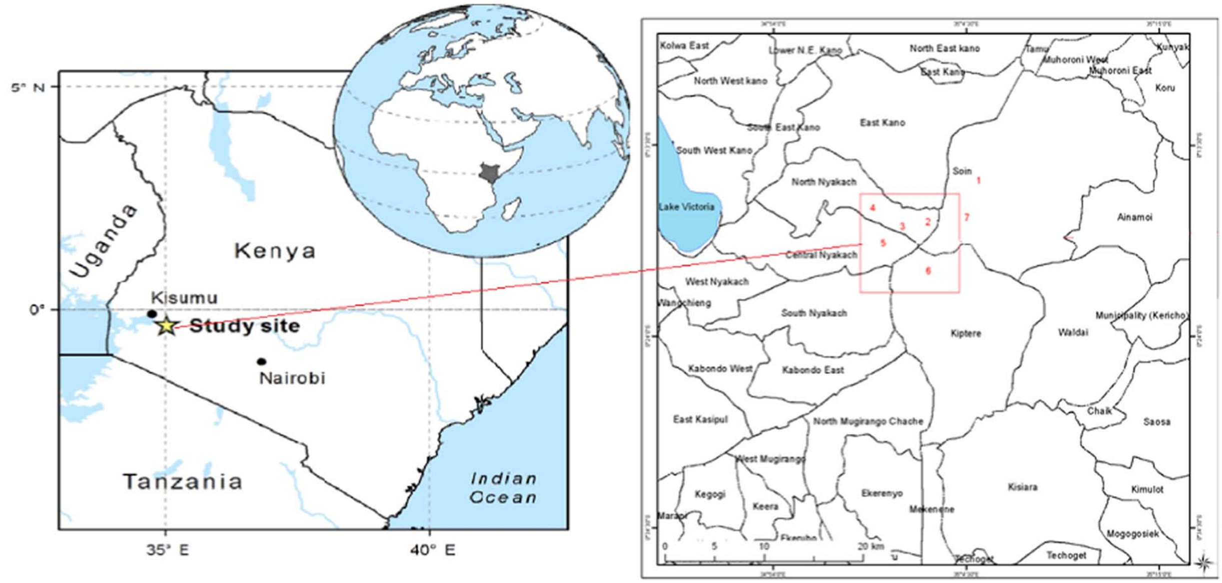

Fig. 1. Study area – lower Nyando, Western Kenya. Left map shows country and region position. Right map shows the administrative boundaries in the study area and numbers indicate the location of villages included in the livestock emission survey.

1991), finger millet (Reddy et al., 2003), beans (Acosta Díaz et al., 2008), groundnuts (Kiniry et al., 2005), and green grams (Kumar et al., 2013). Yields of Napier grass were estimated by multiplying the area under cultivation by published estimates for the yield of Napier under field conditions (Van Man and Wiktorsson, 2003). Yields of minor feedstuffs (e.g.: banana stems) were estimated from farmer recall regarding the amount and frequency of feeding.

2.4. Determination of diet quality and seasonal "feed basket"

Feed resources (i.e., pasture, crop stovers, Napier grass, etc.) were pooled by type of feed for the farms surveyed in each zone and each season and the representation of each feedstuff in the notional diet was deemed to be proportional to the availability of the different plant biomass in each zone/season. The DM, Organic Matter (OM), Crude Protein (CP), Neutral and Acid Detergent Fibre (NDF, ADF), and Ether Extract (EE) concentrations in feed samples were determined by wet chemistry and have been published elsewhere (Onyango et al., 2017). Dry matter digestibility (DMD) was estimated using the equation of Oddy et al. (1983):

$$DMD\ (\text{g}/100\ \text{gDM}) = 83.58 - 0.824{*}\text{ADF}\ (\text{g}/100\ \text{gDM}) + 2.626{*}\text{N}\ (\text{g}/100\ \text{gDM}) \quad (1)$$

Seasonal mean dry matter digestibility (SMDMD) of diets was estimated using the equation:

$$\text{SMDMD} = \sum \frac{\%\text{diet of individual feedstuff}{*}\%\text{DMD of the feedstuff}}{100} \quad (2)$$

2.5. Estimation of cattle energy expenditure

Energy expenditure was determined for each animal for each season. Total energy expenditure was deemed to be equal to the sum of MER for Maintenance (MER_M) plus MER for Growth (MER_G) (minus for weight loss) plus MER for lactation (MER_L) plus MER for travel and ploughing/traction (MER_T and MER_P). Energy requirement for thermoregulation was not considered, because in the area surveyed environmental conditions were such that animals should mostly have been in a thermo-neutral zone year round (Mean annual temperature:17.0 (min)–29.4 (max) °C). Energy requirements for gestation were not specifically included, as this is only of significance with respect to energy requirements in the final 8–12 weeks of gestation and is partly captured in the dam's LW change. Calves under 3 months were treated as pre-ruminant (therefore not emitting CH_4) and the milk required for their maintenance and growth attributed to the milk production of the dam and included in the total energy expenditure for the dam. Calves over the age of three months were deemed to be weaned and on pasture. All equations for the estimation of the various components of MER have been derived from equations adopted by the CSIRO publication, "Nutrient Requirements of Domestic Ruminants" (CSIRO, 2007) (NRODR), unless otherwise stated. As typical diets for smallholders ruminants were overwhelmingly roughage based, where relevant equations pertaining specifically to forages have been used.

2.5.1. Estimation of energy requirements for maintenance (MER_M)

The equation for the estimation of MER_M is based on equations (1.20, 1.21 and 1.12A) in NRODR (CSIRO, 2007). The final resulting equation is:

$$\text{MER}_\text{M}(\text{MJ/d}) = \text{K}{*}\text{S}{*}\text{M}{*}\frac{(0.26{*}\text{MLW}^{0.75}{*}\exp^{(-0.03{*}\text{A})}}{\left(0.02{*}{}^{\text{M}}\!/_{\text{D}}\right) + 0.5} \quad (3)$$

Where: K = 1.3 (intermediate value between that given for *B. taurus* and *B. indicus*); S = 1 for females & castrates, 1.15 for males; M = 1 (0% milk in diet); MLW = mid-term LW (LW at end of season + LW beginning of season)/2 in kg); A = age (in years); DMD = Dry Matter Digestibility (g/100 g); M/D = 0.172 * DMD − 1.707 (MJ ME/kg DM) (i.e.: metabolizable energy content.

2.5.2. Estimation of energy requirements for growth (MER_G)

Two equations were required to account for LW change (equations 1.29 and 1.36 in NRODR (CSIRO, 2007)). Daily LW gain (/loss) was determined as:

$$\text{LW}_\text{change}(\text{kg/d}) = \frac{\text{LW}_\text{end of season}(\text{kg}) - \text{LW}_\text{start of season}(\text{kg})}{\text{Number of days between measurements}} \quad (4)$$

and deemed to be constant for the whole season.

Due to adverse weather conditions during the final measurement period, it was not possible to reach farmers transporting the mobile scale. Subsequently, a final LW was estimated by the equation:

$$LW_{end\ observation\ period\ 4} = \frac{LW_{Start\ Period\ 4}\,(kg)}{LW_{End\ Period\ 2}(kg)} * LW_{Change\ Period\ 2}(kg/d) * 92\ (d/period) + LW_{Start\ Period\ 4} \quad (5)$$

If weight change over the observation period was positive then:

$$MER_G(MJ/d) = \frac{(LW_{change} * 0.92 * EC)}{(0.043 * M/D)} \quad (6)$$

If negative:

$$MER_{-G}(MJ/d) = \frac{(LW_{change} * 0.92 * EC)}{0.8} \quad (7)$$

Where:

EC (MJ/kg) = energy content of the tissue (which was taken as a mid-range value of 18 MJ/kg and used in all cases) (NRODR) (CSIRO, 2007). Energy required for pregnancy was not considered separately, but was deemed to be captured in LW change.

2.5.3. Estimation of energy requirements for lactation (MER_L)

Daily Milk Yield (DMY) was calculated as:

$$DMY\ (l/d) = \frac{\text{Mean daily milk production (l)} * \text{N of days in milk}}{\text{d in season (i. e. 92)}} \quad (8)$$

Energy requirements for lactation were calculated using the equation (1.43) given in NRODR (CSIRO, 2007) as:

$$MER_L = \frac{DMY * ECM}{(0.02 * M/D) + 0.04} \quad (9)$$

where: DMY (kg) = Eq. (8); ECM (MJ/kg) = energy content of milk (taken as 3.054 MJ/kg (CSIRO, 2007) due to a lack of data regarding constituents);

Milk consumed by pre-ruminant calves was estimated from work of Radostits and Bell (1970). It was assumed that calves grew at 50 g/day. Daily milk consumption was calculated as follows:

$$\text{Daily milk consumption (l/d)} = LW_{Calf}\,(kg) * 0.107 + 0.143 \quad (10)$$

2.5.4. Estimation of energy expenditure for locomotion (MER_T)

Energy expenditure for locomotion varies with animal husbandry practices, which were generally similar within the three studied topographic zones (Lowland, Slopes, Highlands). Estimates of daily travel were made by fitting an animal in each of three villages from each topographic zone with global positioning recorders (Allan et al., 2013) for 24 h over three consecutive days. Estimates of travel for animals in each zone were derived from position data by taking the mean distance travelled by animals in a zone. Energy expenditure from travel was calculated following NRODR (CSIRO, 2007) as:

$$MER_T(MJ) = DIST\ (km) * MLW\ (kg) * 0.0026 \left(\frac{MJ}{kgLW}/km\right) \quad (11)$$

Where: DIST = distance travelled (km); MLW = mid-term LW and 0.0026 is the energy expended (MJ/(kg LW/km)).

Values for energy expenditure from traction or ploughing are not well characterized in the literature. Lawrence and Stibbards (1990) calculations suggest an energy expenditure for walking of 2.1 J/m/kg LW and a work efficiency for ploughing of 0.3 for Brahman cattle. Singh (1999) suggested that cattle may maintain a traction effort equivalent to 12% of their LW, at a speed of 0.6–1.0 m/s. This indicates additional energy expenditure of 0.4 J/m/kg LW. From the above it may be inferred that ploughing requires (at 0.8 m/s velocity) 0.002 MJ/h/kg LW.

Thus, energy expenditure from ploughing was calculated as:

$$MER_P(MJ) = \text{Work Hours (h/d)} * days_{work} * MLW\ (kg) * 0.002\ (MJ) \quad (12)$$

Days and day length worked was based on farmer recall.

2.6. Calculation of emission factors (EF)

Firstly, dry matter intake (DMI) was calculated as:

$$DMI\ (kg/d) = \frac{MER_{Total}}{GE * MSDMD * 0.81} \quad (13)$$

where: MER_{Total} = sum of all animal energy requirements (i.e. maintenance, locomotion, ploughing, lactation, etc.); GE = Gross Energy concentration of the diet (assumed to be 18.1 MJ/kg DM, a mid-range value for tissue (CSIRO, 2007)); and 0.81 was the factor to convert Metabolizable Energy to Digestible Energy (see CSIRO, 2007).

Daily Methane Production (DMP) was calculated as follows:

$$DMP\ (g/d) = 20.7 * DMI\ (kg) \quad (14)$$

using the conversion factor of Charmley et al. (2016). Annual CH_4 production (i.e., the EF) for each class of animal was calculated by multiplying seasonal DMP by 92 and by summing all seasons.

3. Results

The initial survey showed 416 cattle of all classes present in the 60 households surveyed. Given the numbers present analysis was performed for all categories of cattle. Locomotion data was not included for calves, as these generally were observed to be kept around the homestead. Energy expenditure for traction was calculated only for mature males, as no farmers in the study used females or immature males for ploughing. Cattle numbers changed by season in all three regions, due to the combined effects of informal loaning ("giving" of animals to relatives), births, deaths, commercial sales, and purchases (Table 1). When an animal was present for measurement it was considered to be "on-farm" for the whole of that season. Adult mortality was 7.0% and calf mortality 18.3% for the one year period of the survey.

LW showed little seasonal variation across the year, but there were major differences in LW between classes in a region and within classes between regions (Table 2).

The seasonal feed basket (Table 3) showed modest variations in DMD (55.9–64.1%), which may have been due to a predominant reliance on pasture in most seasons and zones.

Estimates of MER and of total daily mean metabolizable energy expenditure are given in Tables 4–8 for all the five cattle categories. Based on this information the calculated EFs ranged from 19.3 to 37.4 kg CH_4 per annum depending on location and class for adolescent and adult animals and 13.9–20.4 kg for calves < 1 year old (Table 9).

4. Discussion

The mean EFs derived from the present study are substantially lower for adolescent and adult male (30.1, 35.9 versus 49 kg CH_4) and for adolescent and adult female (23.0, 28.3 versus 41 kg), but not calves (15.7 versus 16 kg) than those given for "other" African cattle in IPCC (Tier I) estimates (Dong et al., 2006). This was surprising given that MER_M (which is directly proportional to LW) was the predominant energy demand in our calculations and the mean LW of females in our study was similar to the "typical" female weight for African cattle used in Tier I. However, male animals were ~25% lighter than the male LW used in the IPCC information (Table 10A.2). Because the approach to develop TIER II EFs here is basically the same as the approach given by the IPCC, that is to say:

$$CH_4 = \text{Energy intake}^* \ Y_m \ (\text{“methane conversion factor”})$$

it follows that either the calculation of energy intake or Y_m or both must vary substantially from the IPCC approach.

The alternative equation for methane production rate (MPR- CH_4 g/d) developed by Charmley et al. (2016) and equivalent to the equation used in this study, at 6.3% of gross energy intake (GEI) is in close

Table 1
Cattle population, by class and topographic zone, showing births, deaths, purchases sales and loans over the (12 month) survey period.

Topographic zone	Category	Season				Management				
		Short dry	Short wet	Long dry	Long wet	Births	Deaths	Sales	Purchases	Loans
Highlands	Males 1–2 years old	6	3	2	1	n.a.	0	5	0	0
	Males > 2 years old	11	7	7	3	n.a.	0	3	1	5
	Females 1–2 years old	3	3	3	3	n.a.	1	0	1	0
	Females > 2 years old	27	26	25	25	n.a.	2	2	2	1
	Calves	25	24	25	21	10	8	7	1	0
	Total	72	63	62	53	10	11	17	5	6
Lowlands	Males 1–2 years old	13	10	11	10	n.a.	0	5	1	0
	Males > 2 years old	22	16	18	16	n.a.	2	7	3	0
	Females 1–2 years old	11	10	7	7	n.a.	1	2	0	1
	Females > 2 years old	42	42	43	43	n.a.	1	1	3	0
	Calves	34	31	42	38	9	5	2	2	0
	Total	122	109	121	114	9	9	17	9	1
Slopes	Males 1–2 years old	15	10	6	4	n.a.	0	5	0	0
	Males > 2 years old	41	34	36	28	n.a.	1	7	8	1
	Females 1–2 years old	9	8	9	6	n.a.	0	2	2	1
	Females > 2 years old	85	70	68	56	n.a.	2	12	4	9
	Calves	72	65	53	43	5	11	18	3	2
	Total	222	187	172	137	5	14	44	17	13
Sum study region (Nyando)	Males 1–2 years old	34	23	19	15	n.a.	0	15	1	0
	Males > 2 years old	74	57	61	47	n.a.	3	17	12	6
	Females 1–2 years old	23	21	19	16	n.a.	2	4	3	2
	Females > 2 years old	154	138	136	124	n.a.	5	15	9	10
	Calves	131	120	120	102	24	24	27	6	2
	Total	416	359	355	304	24	34	78	31	20

n.a. = not applicable to category.

Table 2
Seasonal mean live weights (SEM) (kg) of the five classes of cattle (females > 2 years old, 1–2 years old, males > 2 years old, males 1–2 years old, calves < 1 year old) from three topographic zones of the Nyando basin, Kenya.

Category/topographic zone	Short dry season	Short wet season	Long dry season	Long wet season
Females > 2 years old				
Highlands	277.2 (9.5)	272.8 (9.1)	263.6 (9.2)	256.0 (9.6)
Lowlands	180.4 (4.2)	187.6 (4.0)	186.5 (4.5)	186.9 (5.5)
Slopes	215.4 (3.7)	219.9 (4.1)	213.8 (4.5)	213.5 (5.5)
Mean	216.3 (3.8)	220.6 (3.9)	214.5 (3.9)	214.2 (4.4)
Females 1–2 years old				
Highlands	202.1 (37.1)	235.2 (30.8)	242.2 (31.9)	246.8 (32.5)
Lowlands	126.5 (8.1)	136.7 (8.9)	141.3 (13.2)	141.2 (15.0)
Slopes	140.9 (14.3)	157.2 (16.4)	160.9 (14.8)	169.5 (19.7)
Mean	143.8 (9.8)	160.9 (11.2)	168.9 (12.5)	174.1 (14.8)
Males > 2 years old				
Highlands	262.2 (9.1)	259.7 (15.4)	245.9 (20.2)	222.6 (5.9)
Lowlands	196.0 (5.7)	205.6 (7.9)	188.5 (9.0)	179.3 (9.2)
Slopes	216.1 (7.2)	226.4 (7.8)	214.9 (7.2)	218.1 (8.6)
Mean	216.9 (5.1)	224.2 (5.8)	209.4 (5.8)	204.1 (6.5)
Males 1–2 years old				
Highlands	197.1 (33.4)	194.3 (28.1)	169.9 (8.5)	158.7 (n.a.)
Lowlands	116.1 (9.5)	126.6 (12.4)	130.5 (9.1)	140.6 (9.1)
Slopes	138.8 (8.5)	153.8 (12.6)	147.4 (13.5)	163.5 (15.2)
Mean	140.5 (9.1)	147.3 (9.4)	140.0 (7.2)	149.0 (7.6)
Calves < 1 year old				
Highlands	83.4 (8.7)	90.1 (11.4)	85.6 (11.8)	90.8 (13.8)
Lowlands	48.5 (4.1)	58.4 (4.1)	69.2 (3.9)	74.7 (4.5)
Slopes	64.4 (4.6)	73.8 (5.4)	76.6 (5.5)	83.6 (6.2)
Mean	63.4 (3.3)	72.6 (4.0)	76.0 (3.7)	81.6 (4.1)

n.a. = not applicable to category.

agreement with the IPCC default estimate of 6.5%. Thus, it seems reasonable to conclude that the major differences in EFs between our method and that of IPCC TIER I occur due to markedly different estimates of voluntary intake. IPCC methodology explicitly assumes that intake is *ad libitum* and bases estimates of intake on diet digestibility and some categorical assumptions on energy expenditure. As stated earlier, the assumption of *ad libitum* intake is frequently violated for African smallholder livestock, due to restrictive husbandry practices including being held in bomas overnight without access to feed or water or the tethering or grazing reduced sward heights during day time (Njarui et al., 2016). We deliberately set out to avoid reliance on the assumption of *ad libitum* intake as we based our estimates on energy expenditure. In our study estimates of energy expenditure were based on repeated animal measurements and using this, combined with knowledge of feed resources available, to estimate intake. This has resulted in lower estimates of GEI and hence, EFs that are considerably lower than Tier 1 estimates. Our study also suggests that animal intakes were well below *ad libitum*, evidenced partly by the frequently observed seasonal LW losses.

The EFs reported in this study were much less than the 76.4 kg and 71.8 kg for dairy and beef cattle, respectively, reported by Du Toit et al. (2014) for livestock systems in South Africa. This might be expected given the LW of these cattle being approximately three times that of the cattle in our study (and that voluntary intake would have been commensurately larger). Kouazounde et al. (2015) reported an average EF of 39 kg for cattle from Benin, although this varied considerably according to breed and body size. By comparison, Swamy and Bhattacharya (2006) have reported EFs of 21–23 kg CH_4 for cattle in India in a similar LW range (175–300 kg) to the present study – although a lower Y_m (4.83–6.0%) appears to have been used.

The DM digestibility's of the individual diet components (Table 3, with further details in Onyango *et al.*, 2017) were in agreement with those calculated by Shem et al. (1995) for typical livestock feeds used by smallholders in northern Tanzania. Our estimates of the average digestibility of the seasonal food basket for smallholder cattle are somewhat greater than the default digestibility (55%) in IPCC estimates, but this does not account for the disparity in EFs between the

Table 3
Composition of seasonal diets and their dry matter digestibility in the three topographic zones of the Nyando basin, Kenya.

Topographic zone	Feedstuff	Short dry season		Short wet season		Long dry season		Long wet season	
		% diet	% DMD	% diet	% DMD	% diet	% DMD	% diet	% DMD
Highlands	Pasture	72.1	64.5	78.2	64.2	83.4	63.5	83.4	59.6
	Banana stems	1.3	54.9	1.3	48.0	1.3	57.4	1.3	48.0
	Napier Grass	14.3	55.5	14.3	56.4	14.3	55.5	14.3	56.4
	Banana leaves	1.0	60.8	1.0	60.8	1.0	60.8	1.0	60.8
	Sweet potato vines	1.9	66.2	0.5	63.7	n.f.	n.f.	n.a.	n.a.
	Maize stover[a]	9.4	55.9	4.7	55.9	n.a.	n.a.	n.a.	n.a.
	Average DMD		59.6		58.2		59.3		56.2
Lowlands	Pasture	93.9	62.4	98.6	64.0	34.7	61.7	100.0	57.7
	Tree leaves[b]	n.f.	n.f.	n.f.	n.f.	55.6	59.3	n.f.	n.f.
	Sugarcane tops	n.f.	n.f.	n.f.	n.f.	9.0	52.9	n.f.	n.f.
	Maize stover[a]	6.1	55.9	1.4	55.9	0.7	55.9	n.a.	n.a.
	Average DMD		59.2		60.0		57.5		57.7
Slopes	Pasture	100.0	63.8	100.0	64.1	90.7	59.9	100.0	56.8
	Sugarcane tops	n.f.	n.f.	n.f.	n.f.	9.3	51.9	n.f.	n.f.
	Average DMD		63.8		64.1		55.9		56.8

DMD = dry matter digestibility; n.a. = not available; n.f. = available, not fed.
[a] Crop residues were predominantly maize stover.
[b] *Balanite aegyptiaca* & *Mangifera indica* ssp.

two systems. The importance of crop residues in the diets of smallholder livestock has been stressed (McDowell, 1988), but this may in some cases be overemphasized – in our study we found that in nearly all locations and seasons, available pasture was (see Table 3) the most important feed resource. The limitations to the precision of our estimates of pasture biomass and quality through the use of exclusion cages are in principal clear, yet difficult to assess in terms of their practical implications (if any). On the one hand, the rapid senescence of tropical grasses after reaching maturity has been clearly demonstrated (Wilson and Mannetje, 1978), implying that our sampling interval may result in the over or under estimation of DMD of pasture for some parts of the year. Another consideration is that constant grazing, whilst potentially increasing DMD, will lead to impaired plant growth and lower production of biomass (Troughton, 1957). Ultimately this must be seen as a potential limitation of the pasture assessment, along with the number and area, of samples to estimate pasture growth, indicating that further work is required. However, other estimates – in particular of the availability of crop stovers and Napier grass were made with a high degree of confidence, because precise areas under cultivation were measured and not subject to such complications as communal grazing. The limited quantities of stovers and Napier grass available for consumption also indicate that animals must derive a large proportion of their energy requirements by feeding on pasture and thus we believe our feed basket composition to be substantially correct.

Surprisingly, there were no clear seasonal trends in the nutritional value (i.e.: digestibility) of pasture, most likely because the samples as harvested showed the effects of early - mature stages of growth and the climatic effects of more than a single season. Similarly, there were no uniform changes in cattle's' LW by landscape position or season, which was also not expected – LW losses for some individuals occurred in all landscape positions in all seasons. The reasons for this are difficult to discern, in part this was probably due to limitations in the sampling protocol – a full month was required to measure the LW of all cattle in the study area, so that while animals were measured from the very start of the season, some would not be weighed until mid-season. Local weather conditions and individual husbandry decisions most likely also played a role in the observed variability in cattle LW flux and highlight the overall heterogeneity of smallholder farming systems.

Table 4
Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of female cattle > 2 years old, for maintenance (MER_M), growth (MER_G), milk production (MER_L), locomotion (MER_T) and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season					Short wet season					Long dry season					Long wet season				
	MER_M	MER_G	MER_L	MER_T	Total	MER_M	MER_G	MER_L	MER_T	Total	MER_M	MER_G	MER_L	MER_T	Total	MER_M	MER_G	MER_L	MER_T	Total
Highlands																				
1st Quartile	26.7	− 4.9	0.0	0.9	31.3	25.9	− 5.3	0.0	0.9	27.6	26.2	− 6.4	0.0	0.9	25.3	25.6	− 3.7	0.0	0.8	24.6
Mean	28.8	− 1.5	15.7	1.0	44.0	28.9	0.9	8.3	1.0	39.7	28.1	− 2.1	8.4	1.0	35.4	27.9	2.1	2.6	1.0	33.6
3rd Quartile	31.6	2.7	20.6	1.2	48.5	31.3	4.7	11.0	1.1	46.2	31.1	− 0.5	13.1	1.1	37.5	31.1	8.6	0.0	1.1	37.9
Lowlands																				
1st Quartile	20.2	− 0.1	0.0	1.2	25.4	20.7	− 0.3	0.0	1.3	27.8	20.4	− 6.3	0.0	0.6	17.7	20.3	− 0.3	0.0	0.6	21.4
Mean	21.6	4.8	7.7	1.4	35.4	22.2	6.1	4.0	1.4	32.9	22.5	− 3.8	1.9	0.7	21.3	22.4	6.0	0.4	0.7	29.5
3rd Quartile	23.2	8.8	11.2	1.5	43.0	23.9	11.3	7.9	1.6	39.7	24.2	− 0.7	3.6	0.8	24.9	24.6	11.8	0.0	0.8	36.2
Slopes																				
1st Quartile	21.8	− 0.5	0.0	1.4	23.7	21.9	− 3.1	0.0	1.5	26.7	22.2	− 1.8	0.0	0.7	23.2	21.5	− 3.4	0.0	0.7	19.8
Mean	23.6	3.4	7.0	1.6	35.6	23.9	0.1	8.4	1.6	34.2	24.5	3.1	1.2	0.8	29.6	24.2	− 0.2	1.1	0.8	26.0
3rd Quartile	25.4	8.5	10.5	1.8	41.8	26.0	2.7	19.2	1.8	43.4	26.7	6.7	0.0	0.9	34.6	26.7	2.8	0.0	0.9	31.0
All Nyando																				
1st Quartile	21.5	− 1.6	0.0	1.2	25.4	21.9	− 2.5	0.0	1.2	27.1	21.7	− 4.4	0.0	0.7	20.4	21.5	− 2.5	0.0	0.7	21.3
Mean	24.0	2.9	8.7	1.4	37.0	24.4	2.1	7.0	1.4	34.9	24.6	− 0.2	2.9	0.8	28.1	24.5	2.3	1.2	0.8	28.8
3rd Quartile	26.1	8.0	12.0	1.7	43.7	26.3	5.5	11.1	1.7	41.3	26.9	2.1	2.8	0.9	33.9	27.0	6.4	0.0	0.9	34.9

Table 5
Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of female cattle 1–2 years old, for maintenance (MER_M), growth (MER_G), locomotion (MER_T) and total energy expenditure (total) from three topographic regions of the Nyando basin, Kenya.

	Short dry season				Short wet season				Long dry season				Long wet season			
	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total
Highlands																
1st Quartile	21.4	8.7	0.6	30.7	25.7	4.6	0.7	31.1	26.1	− 1.8	0.8	27.5	26.8	5.4	0.8	33.1
Mean	23.9	13.6	0.7	38.2	27.9	7.1	0.8	35.9	28.4	0.3	0.9	29.5	29.4	7.8	0.9	38.1
3rd Quartile	28.6	20.4	0.9	49.9	31.7	10.7	1.0	43.4	32.3	2.0	1.0	31.5	33.4	10.9	1.0	45.4
Lowlands																
1st Quartile	15.9	3.3	0.8	21.8	16.9	2.5	0.5	19.9	17.1	− 4.2	0.4	13.0	16.4	2.5	0.4	18.9
Mean	17.5	5.4	0.9	23.7	18.3	4.3	0.9	23.5	18.7	− 3.4	0.5	15.8	18.5	4.6	0.5	23.6
3rd Quartile	18.7	6.8	1.0	25.3	19.4	5.8	1.1	26.3	20.6	− 2.8	0.6	18.5	20.6	6.6	0.6	28.2
Slopes																
1st Quartile	15.5	0.8	0.8	19.0	16.8	2.0	0.9	24.8	17.7	0.0	0.4	19.0	19.0	4.2	0.5	22.4
Mean	18.9	3.4	1.1	23.4	20.5	6.5	1.2	28.2	21.8	1.9	0.6	24.4	22.6	8.4	0.5	27.1
3rd Quartile	22.5	6.0	1.3	29.9	24.7	9.5	1.5	32.0	25.5	3.6	0.7	27.3	26.2	11.2	0.7	36.8
All Nyando																
1st Quartile	15.9	2.6	0.8	21.4	17.3	2.4	0.8	22.2	17.7	− 3.1	0.4	17.2	18.3	2.6	0.5	21.5
Mean	19.3	6.5	0.9	26.8	21.2	5.6	0.9	27.7	22.2	− 0.6	0.6	22.2	22.6	6.5	0.6	28.5
3rd Quartile	22.0	7.8	1.0	29.9	24.8	9.4	1.1	31.7	26.1	1.6	0.8	27.5	27.5	10.8	0.8	36.1

Table 6
Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of male cattle > 2 years old, for maintenance (MER_M), growth (MER_G), locomotion (MER_T) and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season				Short wet season				Long dry season				Long wet season			
	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total
Highlands																
1st Quartile	40.4	− 2.0	0.9	37.8	41.0	− 0.3	0.9	41.8	38.7	− 0.2	1.1	38.8	37.6	− 2.4	0.8	36.1
Mean	43.2	− 1.8	1.3	42.7	43.6	0.7	1.0	45.3	42.3	− 0.5	1.4	42.0	38.4	− 1.7	0.8	37.6
3rd Quartile	47.1	0.0	1.5	48.3	47.6	1.2	1.1	50.3	47.5	0.0	1.7	45.7	39.5	− 1.3	0.8	38.9
Lowlands																
1st Quartile	33.7	0.0	1.5	35.5	35.7	− 2.4	1.5	34.0	34.4	− 5.7	1.8	28.2	32.7	− 3.8	1.3	29.8
Mean	34.9	7.4	1.7	44.0	36.6	2.5	1.6	40.6	35.3	− 4.7	2.0	31.5	34.0	1.8	1.4	37.2
3rd Quartile	37.1	17.1	2.1	52.3	39.0	10.0	1.8	48.5	38.5	− 1.0	2.4	34.2	36.9	9.0	1.5	45.1
Slopes																
1st Quartile	33.8	0.0	1.5	37.1	34.4	− 0.6	1.5	35.8	35.9	− 3.1	1.9	35.8	36.2	− 0.5	1.4	36.9
Mean	37.2	5.4	1.8	44.4	38.3	2.7	1.7	41.6	38.5	− 0.6	2.4	40.3	38.6	0.6	1.6	40.9
3rd Quartile	40.9	10.5	2.1	48.9	41.5	5.9	1.9	46.1	41.8	0.5	2.9	44.1	41.9	0.8	1.8	45.9
All Nyando																
1st Quartile	34.0	0.0	1.4	36.9	35.8	− 0.7	1.4	36.0	35.3	− 4.2	1.7	33.2	33.8	− 1.7	1.2	34.3
Mean	37.6	4.8	1.7	44.0	38.7	2.4	1.6	41.9	38.1	− 1.8	2.1	37.6	37.0	0.8	1.5	39.2
3rd Quartile	40.7	8.9	2.1	49.2	41.3	5.7	1.8	48.1	41.5	0.0	2.6	42.3	40.0	2.0	1.7	44.0

Despite the absence of uniform trend(s), it is clear that most animals were in energy deficit for part of the year and mobilizing body reserves to meet energy requirements. Taking account of these losses was an important factor in assessing intakes and ultimately DMP. An important limitation in assessing MER_G was a lack of knowledge of the tissue composition of the LW gain, which can vary from 8.5–29 MJ/kg (CSIRO, 2007). Algorithms based on breed type and growth stage exist to estimate composition (Corbett et al., 1987), but such data was not available for the population studied, so a mid-range value was employed, with unknown error. Milk composition was not measured in this study; however, such knowledge would produce better estimates of the energy expended during lactation and improve the precision of intake estimation in lactating animals. A significant feature of rain-fed systems is the variability in biomass production due to variance in rainfall. In this study we examined animal production over one full year only, whereas Herd et al. (2015) have suggested that up to five years data is required to sufficiently capture the variability in rain-fed pasture systems to provide reliable estimates of ruminant GHG emissions.

5. Conclusions

In this study, we avoided the need to rely on the assumption of *ad libitum* intake to estimate daily methane production by cattle by deriving energy expenditure from production parameters, which allowed us to produce more reliable estimates of intake, and ultimately CH_4 production by smallholder cattle. Based on this new approach, which is appropriate for smallholder livestock systems, we calculated EFs up to 40% less than existing TIER I estimates. Nevertheless, it needs to be stressed our study is the first of its kind for Sub-Sharan Africa relying on animal measurements, which should not automatically be extrapolated outside of its geographic range. It does however, point out the need for further measurements, and highlights the value of using a robust methodology which does not rely on the (often invalid) assumption of *ad libitum* intake in systems where intake is known or likely to be restricted.

Table 7
Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of male cattle 1–2 years old, for maintenance (MER_M), growth (MER_G), locomotion (MER_T) and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season				Short wet season				Long dry season				Long wet season			
	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total	MER_M	MER_G	MER_T	Total
Highlands																
1st Quartile	32.2	0.0	0.7	34.6	33.9	1.8	0.6	40.5	33.5	− 1.2	0.8	33.9	32.9	3.5	0.6	37.0
Mean	37.2	0.8	0.9	38.9	37.6	4.0	0.7	42.3	34.3	0.7	1.0	36.0	32.9	3.5	0.6	37.0
3rd Quartile	45.8	0.0	1.0	46.9	39.8	6.0	0.8	44.8	35.0	2.7	1.1	38.2	32.9	3.5	0.6	37.0
Lowlands																
1st Quartile	20.1	0.0	0.6	28.8	23.9	1.7	0.8	28.6	25.2	− 2.3	0.8	23.9	27.1	0.5	0.9	31.4
Mean	25.2	7.3	0.9	33.4	27.4	4.8	1.0	33.2	28.0	− 0.2	1.2	28.3	29.2	4.4	1.0	34.7
3rd Quartile	28.0	9.0	1.1	34.3	29.0	6.8	1.1	34.9	29.5	0.4	1.1	29.3	30.1	6.7	1.1	39.0
Slopes																
1st Quartile	25.4	0.0	1.0	27.6	27.0	0.5	0.7	24.1	27.2	0.3	1.0	30.3	31.4	− 0.1	1.1	32.4
Mean	28.1	7.6	1.1	36.8	30.4	4.5	0.9	27.8	30.6	3.2	1.2	34.2	32.9	0.5	1.2	34.5
3rd Quartile	31.1	12.2	1.3	41.2	34.0	6.5	1.3	39.7	32.7	5.2	1.2	38.9	34.6	0.6	1.3	36.5
All Nyando																
1st Quartile	24.8	0.0	0.8	28.8	25.1	1.6	0.7	28.8	25.6	− 1.3	0.8	27.1	28.6	0.2	0.8	33.1
Mean	29.0	5.8	1.0	35.9	30.3	4.5	0.9	32.6	29.6	0.7	1.1	30.9	30.6	3.2	1.0	35.0
3rd Quartile	32.5	9.0	1.2	41.0	34.2	6.6	1.1	40.3	33.0	2.1	1.1	35.3	32.9	4.2	1.1	38.2

Table 8
Seasonal mean, 1st and 3rd quartiles for daily metabolizable energy requirements (MER, MJ/d) of calves < 1 year old, for maintenance (MER_M), growth (MER_G), and total energy expenditure (total) from three topographic zones of the Nyando basin, Kenya.

	Short dry season			Short wet season			Long dry season			Long wet season		
	MER_M	MER_G	Total	MER_M	MER_G	Total	MER_M	MER_G	Total	MER_M	MER_G	Total
Highlands												
1st Quartile	9.53	0.00	13.13	9.05	2.25	9.11	8.14	0.00	8.29	8.89	2.93	11.12
Mean	16.20	6.30	22.26	17.48	7.00	23.17	16.76	2.02	18.78	17.79	7.33	25.12
3rd Quartile	22.35	10.72	31.29	25.94	10.40	34.19	25.83	3.89	25.89	24.84	10.43	36.81
Lowlands												
1st Quartile	8.00	0.00	12.46	10.11	3.49	14.52	12.30	− 0.80	12.47	14.30	1.85	16.74
Mean	11.15	5.17	16.31	12.90	6.23	19.13	14.86	1.17	16.03	15.72	6.19	21.91
3rd Quartile	13.96	8.67	19.50	14.68	8.63	24.24	17.26	3.24	21.29	19.40	9.41	27.05
Slopes												
1st Quartile	8.38	0.00	9.34	9.09	1.66	12.62	11.24	1.07	13.99	12.73	2.81	17.23
Mean	13.30	4.99	18.29	14.74	4.06	18.74	15.96	4.96	20.93	17.04	5.16	22.20
3rd Quartile	17.25	9.12	24.32	19.31	5.75	23.96	20.24	7.22	26.68	20.38	7.08	28.29
All Nyando												
1st Quartile	8.49	0.00	10.57	9.56	2.15	12.73	11.00	0.00	12.41	11.64	2.77	16.74
Mean	13.31	5.28	18.57	14.80	5.24	19.77	15.84	3.11	18.93	16.80	5.99	22.79
3rd Quartile	17.39	9.10	24.05	19.31	7.73	25.00	19.80	5.76	25.06	20.74	8.75	28.47

Table 9
Mean live weight (kg) and emission factors (CH_4 kg/animal/annum) for the five classes of cattle in the three topographic zones of the Nyando basin, Kenya.

Topographic zones	Females > 2 years old		Females 1–2 years old		Males > 2 years old		Males 1–2 years old	Calves < 1 year old		
	Live weight (kg)	Emission factors (CH_4 kg/yr)	Live weight (kg)	Emission factors (CH_4 kg/yr)	Live weight (kg)	Emission factors (CH_4 kg/yr)	Live weight (kg)	Emission factors (CH_4 kg/yr)	Live weight (kg)	Emission factors (CH_4 kg/yr)
Highlands	267.3	34.1	220.6	31.7	249.2	37.4	180.0	34.5	87.5	18.1
Lowlands	185.0	26.7	128.4	19.3	196.0	34.1	129.1	28.9	62.7	13.9
Slopes	215.7	27.1	157.1	23.5	219.5	36.6	139.5	27.8	74.6	16.1
Mean	216.3	28.3	154.6	23.0	216.0	35.9	143.5	30.1	73.4	15.7

Acknowledgements

Funding for this study was provided by the German Federal Ministry for Economic Cooperation and development (BMZ) and the German Technical Cooperation (GIZ) as part of their program: 'Green innovation centres for the agriculture and food sector' and the project '*In situ* assessment of GHG emissions from two livestock systems in East Africa – determining current status and quantifying mitigation options'. A. Onyango was supported by a scholarship granted by the German Academic Exchange Service (DAAD).

References

Acosta Díaz, E., Acosta Gallegos, J., Ramírez, A., Padilla Ramírez, J., 2008. Relationship between the leaf area index and yield of dry bean grown under rainfed conditions. Agricultura Técnica en México 34, 13–20.

AGRA, 2017. Africa Agriculture Status Report: The Business of Smallholder Agriculture in Sub-Saharan Africa: Alliance for a Green Revolution in Africa (AGRA). Issue 5 Nairobi, Kenya.

Allan, B.M., Arnould, J.P.Y., Martin, J.K., Ritchie, E.G., 2013. A cost-effective and informative method of GPS tracking wildlife. Wildl. Res. 40, 345–348.

Ayantunde, A.A., Fernández-Rivera, S., Hiernaux, P.H., Tabo, R., 2008. Implications of restricted access to grazing by cattle in wet season in the Sahel. J. Arid Environ. 72, 523–533.

Bodansky, D.M., Hoedl, S.A., Metcalf, G.E., Stavins, R.N., 2016. Facilitating linkage of climate policies through the Paris outcome. Clim. Pol. 16, 956–972.

Charmley, E., Williams, S.R.O., Moate, P.J., Hegarty, R.S., Herd, R.M., Oddy, V.H., Reyenga, P., Staunton, K.M., Anderson, A., Hannah, M.C., 2016. A universal equation to predict methane production of forage-fed cattle in Australia. Anim. Prod. Sci. 56, 169–180.

Corbett, J., Freer, M., Nolan, J., 1987. In: Jarrige, R., Alderman, G. (Eds.), Feed Evaluation and Protein Requirement Systems for Ruminants, pp. 69–80.

CSIRO, 2007. Nutrient Requirements of Domesticated Ruminants. CSIRO publishing.

Dong, H., Mangino, J., McAllister, T., Hatfield, J., Johnson, D., Lassey, K., de Lima, M., Romanovskaya, A., 2006. Chapter 10: emissions from livestock and manure management. In: IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 4: Agriculture, Forestry, and Other Land Use. IPCC, Paris, France, pp. 10.1–10.87. Available at. http://www.ipcc-nggip.iges (Verified 13 May 2016).

Du Toit, C., Meissner, H., Van Niekerk, W.A., 2013. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S. Afr. J. Anim. Sci. 43, 320–339.

Du Toit, C., Meissner, H., Van Niekerk, W., 2014. Direct methane and nitrous oxide emissions of South African dairy and beef cattle. S. Afr. J. Anim. Sci. 43.

Edmonson, A., Lean, I., Weaver, L., Farver, T., Webster, G., 1989. A body condition scoring chart for Holstein dairy cows. J. Dairy Sci. 72, 68–78.

Hay, R., Gilbert, R., 2001. Variation in the harvest index of tropical maize: evaluation of recent evidence from Mexico and Malawi. Ann. Appl. Biol. 138, 103–109.

Herd, R.M., Oddy, V.H., Bray, S., 2015. Baseline and greenhouse-gas emissions in extensive livestock enterprises, with a case study of feeding lipid to beef cattle. Anim. Prod. Sci. 55, 159–165.

Herrero, M., Thornton, P.K., Kruska, R., Reid, R.S., 2008. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. Agric. Ecosyst. Environ. 126, 122–137.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. U. S. A. 110, 20888–20893.

Holechek, J., Vavra, M., Arthun, D., 1982. Relationships between performance, intake, diet nutritive quality and fecal nutritive quality of cattle on mountain range. J. Range Manag. 741–744.

ICPALD, 2013. The Contribution of Livestock to the Kenyan Economy. IGAD Centre for Pastoral Areas and Livestock Development (ICPALD), ICPALD 4/CLE/8/2013.

Kiniry, J., Simpson, C., Schubert, A., Reed, J., 2005. Peanut leaf area index, light interception, radiation use efficiency, and harvest index at three sites in Texas. Field Crop Res. 91, 297–306.

Kouazounde, J.B., Gbenou, J.D., Babatounde, S., Srivastava, N., Eggleston, S.H., Antwi, C., Baah, J., McAllister, T.A., 2015. Development of methane emission factors for enteric fermentation in cattle from Benin using IPCC Tier 2 methodology. Animal 9, 526–533.

Kumar, K., Prasad, Y., Mishra, S., Pandey, S., Ravi, K., 2013. Study on genetic variability, correlation and path Analysis with grain yield and yield attributing traits in green gram [Vigna Radiata (L) Wilczek]. Bioscan 8, 1551–1555.

Lawrence, P.R., Stibbards, R.J., 1990. The energy costs of walking, carrying and pulling loads on flat surfaces by Brahman cattle and swamp buffalo. Anim. Sci. 50, 29–39.

McDowell, R., 1988. Importance of crop residues for feeding livestock in smallholder farming systems. Plant breeding and the nutritive value of crop residues. In: Proceedings of a Workshop. ILCA, Addis Ababa (Ethiopia), pp. 3–27.

Nicholson, M.J., 1987. Effects of night enclosure and extensive walking on the productivity of zebu cattle. J. Agric. Sci. 109, 445–452.

Njarui, D., Gichangi, E., Gatheru, M., Nyambati, E., Ondiko, C., Njunie, M., Ndungu-Magiroi, K., Kiiya, W., Kute, C., Ayako, W., 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.

Norman, M., 1965. Seasonal performance of beef cattle on native pasture at Katherine, N.T. Aust. J. Exp. Agric. 5, 227–231.

Oddy, V., Robards, G., 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: Proceedings of the Second Symposium of the International Network of Feed Information Centres/edited by GE Robards and RG.

Onyango, A., Dickhoefer, U., Butterbach-bahl, K., Goopy, J.P. Seasonal and site variations in nutrient and mineral concentrations and digestibility of pasture vegetation and supplement feedstuffs for ruminants in Lower Nyando, Western Kenya. J. Asian Australianasian Animal Sci. (Submitted).

Prihar, S., Stewart, B., 1991. Sorghum harvest index in relation to plant size, environment, and cultivar. Agron. J. 83, 603–608.

Radostits, O., Bell, J., 1970. Nutrition of the pre-ruminant dairy calf with special reference to the digestion and absorption of nutrients: a review. Can. J. Anim. Sci. 50, 405–452.

Reddy, B., Reddy, P.S., Bidinger, F., Blümmel, M., 2003. Crop management factors influencing yield and quality of crop residues. Field Crop Res. 84, 57–77.

Shem, M.N., Ørskov, E.R., Kimambo, A.E., 1995. Prediction of voluntary dry-matter intake, digestible dry-matter intake and growth rate of cattle from the degradation characteristics of tropical foods. Anim. Sci. 60, 65–74.

Singh, G., 1999. Draught animal energy research in India. In: Proceedings of an ATNESA Workshop, September, . http://www.atnesa.org.

Swamy, M., Bhattacharya, S., 2006. Budgeting anthropogenic greenhouse gas emission from Indian livestock using country-specific emission coefficients. Curr. Sci. 91, 1340–1353.

Thornton, P.K., Herrero, M., 2010. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. Proc. Natl. Acad. Sci. U. S. A. 107, 19667–19672.

Torell, R., Bruce, B., Kvasnicka, B., 1998. Methods of determining age of cattle. In: Cattle Producer's Library: CL712. University of Nevada, Reno, NV.

Troughton, A., 1957. The Underground Organs of Herbage Grasses. Commonwealth Agricultural Bureaux, Farnham Royal, Hurley.

Tubiello, F., Salvatore, M., Cóndor Golec, R., Ferrara, A., Rossi, S., Biancalani, R., Federici, S., Jacobs, H., Flammini, A., 2014. Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks. Statistics Division, Food and Agriculture Organization, Rome.

Van Man, N., Wiktorsson, H., 2003. Forage yield, nutritive value, feed intake and digestibility of three grass species as affected by harvest frequency. Trop. Grassl. 37, 101–110.

Verchot, L., Boye, A., Zomer, R., 2008. Baseline Report, Nyando River Basin Western Kenya Integrated Ecosystem Management Project (Findings from the Baseline Surveys). International Centre for Research in Agroforestry Nairobi, Kenya.

Wilson, J., Mannetje, L.t., 1978. Senescence, digestibility and carbohydrate content of buffel grass and green panic leaves in swards. Aust. J. Agric. Res. 29, 503–516.

Zhou, G., Munga, S., Minakawa, N., Githeko, A.K., Yan, G., 2007. Spatial relationship between adult malaria vector abundance and environmental factors in western Kenya highlands. Am. J. Trop. Med. Hyg. 77, 29–35.