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Research article

Comparison of Tier 1 and 2 methodologies for estimating intake and enteric methane emission factors from smallholder cattle systems in Africa: a case study from Ethiopia

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A B S T R A C T

Considering the potential environmental impact of livestock production and the significance of accurate estimation methods, it is crucial to assess the differences between various methodologies. The study compared the gross energy intake (**GEI**) and enteric methane (**CH_4**) emission factors (**EF** = kg CH_4/head/year) of cattle based on three methodologies: Intergovernmental Panel on Climate Change (**IPCC**) Tier 1, IPCC Tier 2 and a modified Tier 2 methodology based on Commonwealth Scientific and Industrial Research Organization ('**CSIRO**') Tier 2. Data were collected from smallholder mixed crop-livestock systems in the upper highland sub-humid to semi-humid (**AEZ-1**) and lower highland sub-humid to semi-humid (**AEZ-2**) zones of North Shewa, Ethiopia, corresponding to the beginning and end of spring, summer, and winter. The results revealed that the IPCC Tier 2 methodology estimated a 39% higher GEI (104 vs 74 MJ/ head/day) and a 51% higher implied EF (50 vs 33 kg CH_4 /head/year) compared to the 'CSIRO' Tier 2 methodology. When compared to the IPCC Tier 1 default values, both the IPCC and 'CSIRO' Tier 2 EF estimates were 20–37% and 37–59% lower, respectively. Furthermore, all cattle categories exhibited variations in implied daily CH_4 production across seasons. As all the GEI were estimated, it is not possible to determine which methodology is more accurate. Therefore, future research should compare predicted intakes and emissions with actual experimental data to ascertain the accuracy of the models.

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Implications

The present study compared two Tier 2 methodologies for estimating gross energy intake and enteric methane emission factors, which represent the amount of enteric methane emitted by individual cattle within a year. The results revealed significant differences between the estimates obtained from two Tier 2 methods. These findings provide valuable insights for researchers, encouraging further experimental studies to determine the accuracy and appropriateness of each method for national inventory purposes.

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Specification table

Subject	Livestock Farming Systems
Type of data	Tables, Figure
How data were acquired	On-farm data collection for live weights feed quantity and quality, and animal productivity and estimation for Efs
Data format	Raw, processed, and calculated data in Microsoft Excel
Parameters for data collection	113 smallholder farms selected through random stratification by location in North Shewa including 313 cattle in two agro-ecological zones (AEZs)
Description of data collection	Five live weight measurements per animal (at the beginning and end of the three seasons in the study area), 3 feed sample collections per locality, 3 milk quality assessments done (one per lactating female every season), daily grazing distance estimated once, and daily milk production recording.
Data source location	North Shewa, Ethiopia
Data accessibility	Repository name: Mendeley Data: https://data.mendeley.com/ Data identification number: https://doi.org/10.17632/h986dxz4vr.3 Direct URL to data: https://data.mendeley.com/datasets/h986dxz4vr/3
Related research article	Jo, N., Kim, J., Seo, S., 2016. Comparison of models for estimating methane emission factor for enteric fermentation of growing-finishing Hanwoo steers. SpringerPlus 5, 1–12.

Introduction

Livestock production in Africa has been identified as a significant contributor to environmental impact (Gerber et al., 2013). In fact, more than 70% of agricultural greenhouse gas (**GHG**) emissions on the continent are attributed to the livestock sector (Tubiello et al., 2014). Among these emissions, methane (**CH_4**) from enteric fermentation has been identified as a major GHG source from agricultural activities in Africa (Graham et al., 2022). Specifically, within the ruminant livestock sector, enteric fermentation of cattle has been recognized as the primary source of CH_4 emissions (Tongwane and Moeletsi, 2021). In order to estimate enteric CH_4 production by cattle, methodologies recommended by the Intergovernmental Panel on Climate Change (**IPCC**) guidelines are widely employed. The IPCC guidelines present a three-tier framework for estimating GHG emissions, ranging from Tier 1 (default values) to Tier 2 (considering diet and energy intake) and Tier 3 (country-specific methodologies and parameter estimates) (Jo et al., 2016).

Greenhouse gas emissions in Ethiopia are significantly contributed by ruminants, primarily through enteric fermentation. Among these emissions, cattle CH_4 emissions, specifically enteric methane, account for a substantial portion, comprising 86% of the total CH_4 emissions from ruminants. Both the mixed crop-livestock and pastoral/agro-pastoral production systems in Ethiopia are responsible for the majority of these emissions, with cattle contributing 82.8%, followed by goats at 7.4%, and sheep at 6.9% (Wilkes et al., 2020). These emissions predominantly originate from indigenous breeds, as the ruminant livestock population in Ethiopia is almost entirely composed of such breeds (CSA, 2020).

The production of enteric CH_4 by ruminants is influenced by various factors, including dietary characteristics such as daily feed intake, diet type, and composition, as well as livestock production factors such as live weight, growth rate, stage of production, reproduction, and feeding conditions (Tubiello et al., 2013). Therefore, accurately estimating enteric CH_4 production requires specific and reliable data that reflect the conditions of the region or country under consideration (Jo et al., 2016). In this regard, emission factors (**EFs**) derived from regional or local data are particularly valuable as they contribute to more precise GHG inventories (Ibidhi et al., 2021). Following the guidelines provided by the IPCC, Tier 2 methodologies are recommended for national GHG inventories in the livestock sector, especially when a specific livestock species is a significant source of emissions (Spurlock et al., 2012).

The utilization of Tier 2 estimates, as opposed to Tier 1 estimates that solely provide fixed values in tabular form, enables more accurate data by incorporating local information pertaining to animal types, production systems, and feeding practices (Dong et al., 2006). In alignment with this approach, Ethiopia's recent national GHG inventory adopted the IPCC Tier 2 methodology to establish EFs for cattle methane fermentation (Wassie et al., 2022). This national inventory revealed substantial disparities between the default Tier 1 and the computed Tier 2 EFs. The implementation of the Tier 2 methodology resulted in a notable reduction in the uncertainties associated with cattle enteric CH_4 EFs, reducing them from approximately ± 50% when employing the Tier 1 method to ± 18% with the Tier 2 method (Wilkes et al., 2020).

The IPCC Tier 2 methodology is widely employed for estimating enteric CH_4 emissions from cattle in various countries. However, an alternative region-specific Tier 2 methodology based on CSIRO (2007) has been proposed by Goopy et al. (2018) specifically for estimating enteric CH_4 EFs in East African smallholder systems, referred to as the Commonwealth Scientific and Industrial Research Organization '**CSIRO**' Tier 2 methodology (Marquardt et al., 2020). The 'CSIRO' Tier 2 methodology takes into account seasonality in feed availability, feed quality, and consequent fluctuations in live weight. In contrast, the IPCC Tier 2 methodology assumes that any reductions in intake and emissions associated with weight loss are offset by increased intake and emissions during periods of BW gain, thus not explicitly considering weight loss (Goopy et al., 2018, IPCC, 2019). Furthermore, the IPCC Tier 2 methodology estimates net energy (**NE**) requirements, whereas the 'CSIRO' Tier 2 methodology employs metabolizable energy requirements (**MER**). However, both methodologies utilize activity data, such as live weight, milk production, BW gain, and other relevant factors, to estimate energy requirements (Jo et al., 2016, Goopy et al., 2018, Ndung'u et al., 2020).

The objective of this study was to compare the gross energy intake (**GEI**) and enteric methane (CH_4) emission factors (EFs) in smallholder cattle systems in Africa, with Ethiopia as the focus country, utilizing local data and different methodologies. The IPCC Tier 2 methodology calculates CH_4 EF by multiplying a CH_4 conversion factor (**Ym**), representing the proportion of gross energy (GE) in feed transformed into CH_4, with daily GEI based on activity data (Jo et al., 2016). On the other hand, the 'CSIRO' Tier 2 methodology calculates CH_4 EF by multiplying CH_4 yield (**MY**) with daily dry matter intake (**DMI**) (CSIRO, 2007, Marquardt et al., 2020). This study provides a comparative analysis of both Tier 2 methodologies and the IPCC Tier 1 methodology in estimating CH_4 emissions from smallholder cattle systems in Africa, using Ethiopia as a case study.

Material and methods

Study site

The study was conducted in North Shewa, an administrative zone located within the Amhara Regional State of Ethiopia (Fig. 1). Based on factors such as rainfall, temperature, and altitude, two major agro-ecological zones (**AEZ**s) were identified: upper highland sub-humid to semi-humid (**AEZ-1**: 2 438–3 048 m. a. s. l, 10–15 °C, and 1 200–1500 mm rainfall) and lower highland sub-humid to semi-humid (**AEZ-2**: 1 829–2 438 m. a. s. l, 15–18 °C, and 1 200–1 500 mm rainfall) (Sombroek et al., 1982, Macharia, 2004). A total of 33 GPS points were randomly selected from these two AEZs, with proximity to roadways (<2 km) as a criterion. Subsequently, 3–4 households were selected from each GPS point based on the consent of farmers and cattle ownership. The sampling strategy resulted in the inclusion of 95 farmers from AEZ-1 and 18 farmers from AEZ-2. The zone exhibits relative

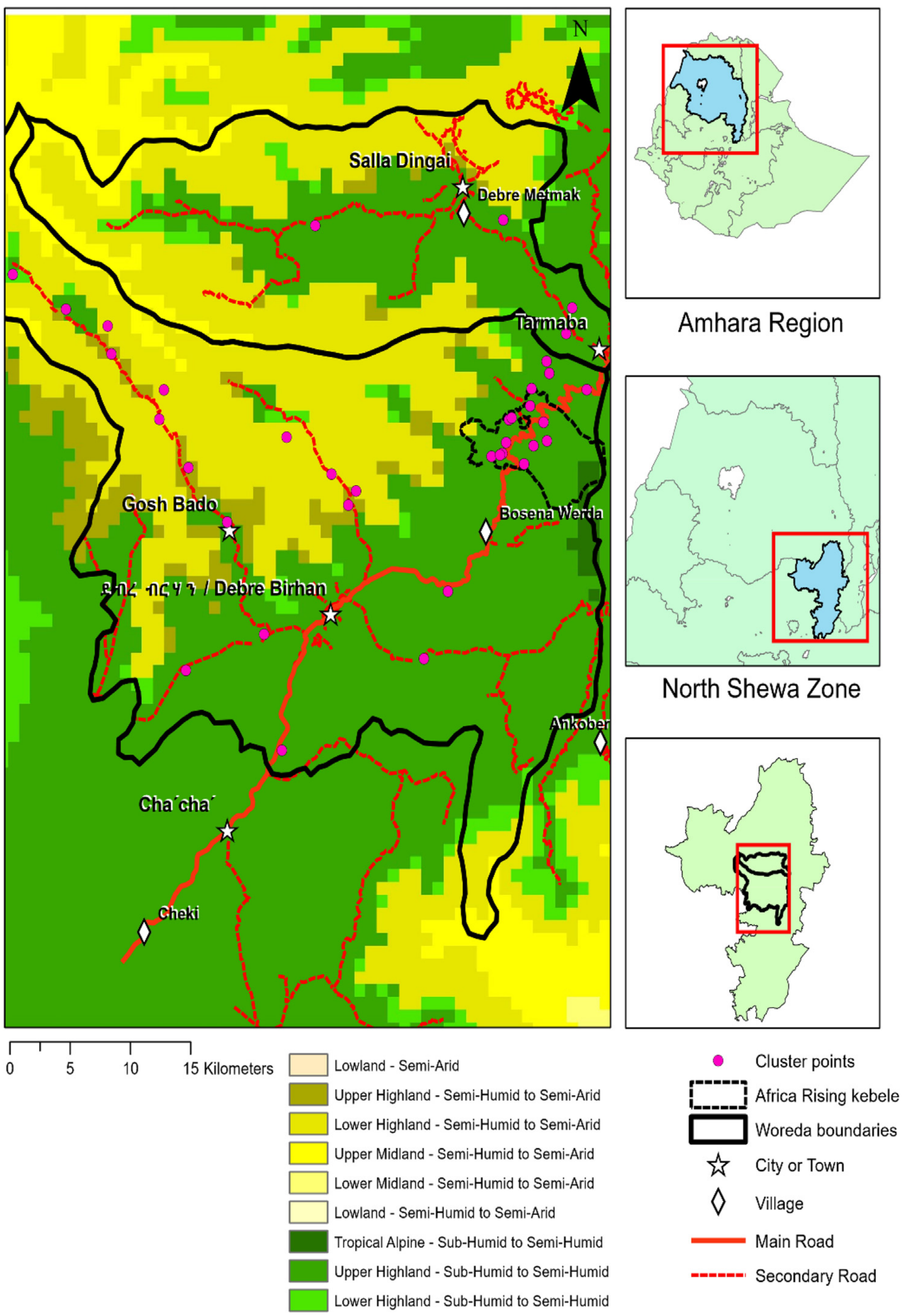

Fig. 1. Study area in North Shewa, Ethiopia. Map shows major agro-ecological zones (AEZs), location of sampling cluster points, woreda (district) boundaries, points of interest, and roads. AEZs are based on Sombroek et al. (1982) and Macharia (2004). Map created in Nairobi, Kenya: M. W. Graham, 19 July, 2023. ArcMap v. 10.6. ESRI Software, USA, 1995–2023.

humidity ranging from 54 to 86% (Timotewos et al., 2022). The landscape positions in the two districts vary in terms of climate, soil type, vegetation, and livestock management, although mixed crop-livestock systems are predominant.

Data collection

Data pertaining to cattle activity, diet, and performance were collected through field surveys conducted from February 2020 to January 2021, utilizing the protocol outlined by Goopy et al. (2018). Upon initial visits to the households included in the study, ear tags (Allflex Europe SA, Vitre, France) were applied to all cattle. The collected data encompassed live weight (**LW**), feed types, overall diet composition, and quality. In accordance with the system employed in the Ethiopian GHG inventory, the study classified cattle into six sub-categories based on their age and sex: calves (<1 year), heifers (1–3 years), young males (1–3 years), intact adult males (>3 years), castrated adult males (>3 years), and adult females (>3 years). Age determination was accomplished using a combination of farmer recall and dentition, following the protocol described by Torell et al. (1998).

To measure the LW of the cattle, a portable animal-weighing scale (Model EKW Endeavour Instrument Africa Ltd., Nairobi, Kenya) was utilized. Live weight data were collected from the farms on four occasions, corresponding to the beginning and end of the three seasons observed at the study sites: (1) spring, the short rainy season (February–May); (2) summer, the main rainy season (June–September), which is also the main cropping season; and (3) winter, the dry season (October–January) (Dawson and Spannagle, 2015). The mean LW for each season was used to calculate seasonal EFs. A total of 313 cattle in AEZ-1 and 65 cattle in AEZ-2 were subjected to measurements. Seasonal weight gain or loss (**LWC**) was estimated by calculating the difference between two consecutive seasons, which was then used to determine the average daily weight gain or loss (**ADWG/L**).

The methodological assumptions employed to measure cattle LW and LWC can be found in Marquardt et al. (2020). In line with IPCC Tier 2, zero weight gain was assumed for adult animals (IPCC, 2019). However, the model necessitates the inclusion of mature body weight (**MBW**) for calves, heifers and young males. MBW refers to the BW at which skeletal development is complete (IPCC, 2019). To estimate MBW for the female animal categories, the average LW of adult cows with a moderate body condition (**BCS** of 2.5 and above) was utilized. For male animals, the weighted average LW of castrated and intact adult males was employed to estimate MBW. The MBW of adult cows was employed to calculate the MBW for female calves and heifers, while the MBW for young males and male calves was estimated using the MBW for adult male animals. Lastly, the MBW for calves was calculated by taking the weighted average of the MBWs of adult cows and adult males, as outlined in Wassie et al. (2022).

The parity (number of previous calvings) and physiological condition (pregnant or lactating) of cows were determined through a combination of farmer recall and direct observations. Information provided by farmers was used to establish the average work hours per day for male cattle. In the 'CSIRO' Tier 2 methodology, the distance traveled during grazing serves as an input parameter. To determine this parameter, GPS collars were fitted to one animal in each village within each topographic zone for a continuous period of 24 h over three consecutive days, following the methodology described by Allan et al. (2013). Calves were not included in the locomotion information as they were observed to be kept in close proximity to the homestead.

Daily milk production in liters during each season was recorded by informed farmers who were provided with a graduated plastic container (1 500 ml jug). The daily milk consumption of preruminant calves ($\leq$3.5 months) (**DCMC**) was determined using the average LW and ADWG of the calves, following the equation described by Radostits and Bell (1970) in Eq. (1):

$$\mathrm{DCMC\ (l)} = 0.107\ \mathrm{(l/kg)} * \mathrm{LW\ (kg)} + 0.00339\ \mathrm{(l/d)} * \mathrm{ADWG\ (g/d)} \tag{1}$$

where DCMC is the daily milk consumption (in l) for preruminant calves; 0.107 (in l/kg calf weight) denotes the amount of milk required for maintenance per kg of calf live weight; LW is the live weight of the calf (in kg); 0.00339 (l /day) is the additional amount of milk required per unit of ADWG; ADWG is the live weight gain of the calf per day (in g).

The total daily milk yield was calculated by combining the daily milk consumption by calves with the average daily milk production. To determine the seasonal average daily milk production, the reported daily milk yield was multiplied by the number of milking days in a season. At the end of each season, pooled milk samples were collected from households with lactating cows. These samples were then analyzed for butter fat (% **BF**), non-fat solids (% **SNF**), and milk density using a lactoscan (Milkotronic Ltd., Bulgaria) in accordance with standard procedure. To convert the average daily milk yield from liters to kilograms, the average density of the milk was used.

To determine the feed baskets at the farm level, feed resources purchased and produced by farmers were combined for each zone and season. The proportion of feed components in the total feed was determined using the protocol outlined by Goopy et al. (2018). The biomass of feed resources produced at the farm level was estimated following the procedure described in Marquardt et al. (2020). In brief, the production of a specific feed type was measured and multiplied by the corresponding growing area. Farmers provided information on farm boundaries, and the areas of individual farms and fields were determined using a laser range finder. The use of the plots was recorded. To estimate pasture yield, an exclusion cage measuring 0.5 meters in height, length, and width was placed per village per season. Pasture yield was measured in 28 villages for AEZ-1 and 5 villages for AEZ-2. The measured yield was then extrapolated to the larger area per village. Every three months, grass up to a height of two centimeters was harvested, weighed, dried, and milled according to standard procedures for quality assessment. The biomass of oat vetch was determined by utilizing published production estimates of 44.5 tons per hectare (**t/ha**) on the wet- matter basis (Beyene et al., 2015). The biomass of crop residue was calculated based on farmer recall of grain yields, which were consistent with previous reports from Mogiso (2017), Shiferaw et al. (2022), Yirgu et al. (2022) and Zegeye et al. (2020). Grain yields were 2.0 t/ha for *Eragrottis* teff, 2.1 t/ha for barley, 2.6 t/ha for wheat, and 4.2 t/ha for peas. Crop residue biomass was estimated by utilizing a conversion factor, which refers to the amount of crop residue generated for a given unit of grain yield (Agegnehu et al., 2012). The conversion factor allows for estimating the quantity of crop residue produced based on the known grain yield. Conversion factors for 'teff', wheat, barley, and peas were taken into account, with values of 3.0, 0.8, 1.2, and 1.0, respectively, as reported by Agegnehu et al. (2012).

Feed samples were dried at 50 °C for 2 days in a forced-air oven and then ground to pass through a 1-mm screen using a hammer mill (MF 10 basic IKA® Werke GmbH & CO. KG, Staufen, Germany). The ground samples were analyzed for dry matter (**DM**), acid detergent fiber (**ADF**) and total nitrogen (**N**). The DM was determined by drying the samples at 105 °C overnight, following an adapted method based on ISO 6496 (1999). Acid detergent fiber analysis was conducted using the methods outlined by Van Soest et al. (1991), with the use of Ankom200 Fiber Analyzer equipment (Ankom Technology Corp., Fairport, NY). Elemental nitrogen in the feed samples was determined through combustion using a CHN analyzer (Elementar Vario MAX cube, Elementar, Langenselbold, Germany) following the Dumas method specified by the Association of Official Analytical Chemists (AOAC, 2006, Method 990.03). Collected feedstuffs were also analyzed for gross energy (**GE**) (MJ/kg DM) using a bomb calorimeter. For each individual feedstuff, the DM digestibility (**DMD**) was calculated using Eq. (2) developed by Oddy et al. (1983).

$$\mathrm{DMD}\ (\mathrm{g}/100\ \mathrm{g\ DM}) = 83.58\text{-}0.824 * \mathrm{ADF}\ (\mathrm{g}/100\ \mathrm{g\ DM}) + (2.626 * N\ (g/100\ g\ DM)) \tag{2}$$

where, DMD is dry matter digestibility (g/100 g DM); 83.58,0.824 and 2.626 are constants; ADF: acid detergent fiber (g/100 g DM); N: nitrogen content (g/100 g DM).

The seasonal mean DMD (**SMDMD**) of the animal diet was calculated using Eq. (3) developed by Goopy et al. (2018).

$$\mathrm{SMDMD} = \frac{\%\ \text{diet of individual feedstuff} \ *\ \%\ \text{DMD of the feedstuff}}{100} \tag{3}$$

where SMDMD (%) denotes the seasonal mean DM digestibility of an animal diet; % diet of individual feedstuff denotes the proportion of each feedstuff in the respective seasonal feed basket; and DMD (%) denotes the DM digestibility of individual feedstuffs calculated using Eq. (2).

To compute EFs using the IPCC Tier 2 approach , the SMDMD was converted to **DE**% (digestible energy expressed as a percentage of gross energy) using Eq. (4) derived from CSIRO (2007).

$$\mathrm{DE}\ (\%) = (0.172 * \mathrm{DMD}\text{-}1.707)/0.81)/\mathrm{GE} * 100 \tag{4}$$

where (0.172*DMD-1.707) is metabolizable energy content of the diet, 0.81 is the factor used to convert metabolizable energy to digestible energy and GE is the energy content of the animal feed (MJ/kg DM).

Estimation of enteric methane emission factors

The enteric CH_4 EFs for cattle categories were estimated using the Tier 2 methodology outlined by IPCC, as per the guidelines provided in the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories (IPCC, 2019). Additionally, 'CSIRO' Tier 2 methodology based on CSIRO (2007) was utilized to generate region-specific enteric methane EFs for cattle kept in smallholder systems (Goopy et al., 2018).

The IPCC Tier 2 methodology employs animal performance and NE requirements to predict GEI (MJ/head/day) (IPCC, 2019).

$$\mathrm{GEI(MJ/day)} = \left[\frac{\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} + \frac{NE_g}{REG}}{\frac{DE\%}{100}}\right] \tag{5}$$

where: GEI = gross energy intake, MJ/day; NE_m = net energy required by the animal for maintenance, MJ/day; NE_a = net energy for animal activity, MJ/day; NE_l = net energy for lactation, MJ/day; NE_{work} = net energy for work, MJ/day; NE_p = net energy required for pregnancy, MJ/day; REM = ratio of net energy available in a diet for maintenance to digestible energy consumed; NEg = net energy needed for growth; REG = ratio of net energy available for growth in a diet to digestible energy consumed; DE%= digestible energy expressed as a percentage of gross energy. Detailed equations to estimate EF using the IPCC Tier 2 methodology are presented in the IPCC (2019) guidelines.

Daily enteric CH_4 production (**DMP**) (kg CH_4/day) for the IPCC Tier 2 method is estimated from GEI as per Eq. (6).

$$\mathrm{DMP(Kg\ CH4\ /day)} = \frac{(\mathrm{GEI}\ * (Y_m/100))}{55.65\ (\mathrm{MJ\ Kg\ CH4})} \tag{6}$$

where DMP is the daily methane production (kg CH_4/day), GEI is gross energy intake in MJ/day, and Y_m is the CH_4 conversion rate (%), which is the percent of GE in feed converted to CH_4. The updated IPCC (2019) Y_m value of 7.0% for cattle was used because forages constitute >97% of the animal diets in all seasons and AEZs.

The 'CSIRO' Tier 2 methodology estimates DMI based on Eq. (7) (Goopy et al., 2018).

$$\mathrm{DMI\ (kg/d)} = \frac{\mathrm{MER_{Total}\ (MJ/d)}}{\mathrm{GE\ (MJ/kg)} * (\mathrm{DMD}/100) * 0.81} \tag{7}$$

where DMI (kg/day) is dry matter intake, MER_{Total} (MJ/day) is the sum of all maintenance energy requirements (i.e., maintenance, locomotion, traction, lactation, etc.), GE (MJ/kg DM) is the gross energy concentration of the diet for each season and agro-ecological zone, as estimated by feed quality analysis, DMD (%) is dry matter digestibility, and 0.81 is the factor used to convert metabolizable energy to digestible energy.

The DMP for the 'CSIRO' Tier 2 methodology is estimated from the estimated DMI using the following equations (Charmley et al., 2016):

$$\mathrm{DMP\ (g\ CH4\ /day)} = 20.7\ (\mathrm{g\ CH4/kg\ DM}) \ *\ \mathrm{DMI\ (kg/d)} \tag{8}$$

where, DMP is the daily methane emission of an animal (g CH_4/day) (CSIRO, 2007). Detailed equations to estimate EFs using the 'CSIRO' Tier 2 approach are presented in Marquardt et al. (2020).

Data management and analysis

Both Tier 2 models were programmed in Microsoft Excel to estimate DMP for each season and cattle category. The annual EFs were calculated as the weighted average of seasonal DMPs. The DMP in each season were compared using analysis of variance (ANOVA) performed in STATA 17. Additionally, a t-test conducted in XLSTAT was used to compare DMPs and EFs between the two models. Statistical significance was set at $P < 0.05$. The EFs were also compared between the two models and with Tier 1 default values. To compare the implied GEI and EFs between the two Tier 2 methodologies, Bland-Altman plots were generated using Microsoft Excel. These plots were used to explore the mean difference between the two methods. The analysis also compared the methane conversion factors between the models by converting calculated DMP values in the 'CSIRO' model to 'Ym', a unit equivalent to Y_m in the IPCC Tier 2 method. This conversion was made by applying Eq. (6) mentioned earlier. To ensure comparability, the IPCC value for the energy content of methane (55.65) was used (IPCC, 2019).

Results

Table 1 shows that the annual average LW in AEZ-1 was higher by 16% for adult females, 11% for young males, 8% for castrates, and 4% for intact males compared to AEZ-2. Daily weight gain or loss was observed in different seasons, with animals gaining more weight during the summer season, which coincides with the main rainy and cropping season (Table S1 in the supplemental material). The average DMD % was found to be highest during summer, followed by spring and winter. AEZ-1 had a 2.6% higher average DMD % (ranging from 54.1% to 56.8%) compared to AEZ-2 (ranging from 53.0% to 56.2%) (Table 2). When compared to Tier 1 default values, the IPCC Tier 2 annual average EFs were 20–37% lower, while the 'CSIRO' Tier 2 EFs were 37–59% lower (Fig. 2). Similarly, total CH_4 emissions were 27% lower with IPCC Tier 2 and 52% lower with 'CSIRO' Tier 2 compared to emissions calculated using the default Tier 1 EF (Fig. 3).

Table 1
Seasonal live weights (mean) (kg) of different classes of cattle: (females >3 years, males (intact and castrates) >3 years, heifers 1–3 years, young males 1–3 years and calves < 1 year) from two agro-ecological zones (AEZ) in North Shewa zone, Ethiopia.

AEZ	Cattle category	Spring		Summer		Winter		Annual Average	
		N	LW (kg)	N	LW (kg)	n	LW (kg)	N	LW (kg)
AEZ-1	Adult Females	106	217	87	221	83	225	93	220
	Males: Intact	74	251	55	232	45	224	58	237
	Males: Castrates	70	292	85	299	84	296	80	295
	Heifers	36	131	35	139	35	149	35	139
	Young males	39	131	28	150	25	161	30	146
	Calves	9	85	16	59	25	70	17	73
AEZ-2	Adult Females	18	174	18	188	17	206	18	189
	Males: Intact	13	227	12	228	9	226	11	227
	Males: Castrates	21	267	22	272	22	281	21	273
	Heifers	4	133	5	144	4	150	4	141
	Young males	9	120	9	137	8	142	9	132
	Calves	2	73	2	58	2	80	2	71
Overall	Adult Females	124	210	105	215	100	221	111	215
	Males: Intact	87	247	67	231	54	224	69	235
	Males: Castrates	91	286	107	293	106	293	101	291
	Heifers	40	131	40	140	39	150	39	140
	Young males	48	129	37	147	33	157	39	144
	Calves	11	83	18	59	27	68	19	72

Abbreviations: AEZ-1: upper highland semi-humid; AEZ-2: lower highland sub-humid to semi-humid; LW: Live weight in kg (kilograms).

Table 2
Seasonal feed baskets for cattle from two agro ecological zones (AEZ) of North Shewa zone, Ethiopia.

		Spring			Summer			Winter		
		% of diet	ADF (%)	DMD (%)	% of diet	ADF (%)	DMD (%)	% of diet	ADF (%)	DMD (%)
AEZ-1	Pasture	64.1	33.7	59.0	65.7	33.5	59.6	53.7	36.0	56.4
	Cut and carry grass	6.8	39.9	52.8	7.1	38.4	54.3	6.0	40.1	52.7
	Wheat straw	9.2	48.6	45.3	7.4	48.5	45.3	10.8	45.4	47.7
	Barley straw	8.7	46.4	46.9	8.8	48.5	45.4	14.6	47.8	45.9
	'Teff' straw	8.4	39.0	53.1	6.3	39.0	53.1	10.5	39.0	53.1
	Pea residue	–			1.7	45.0	48.8	–		
	Wheat bran	–			2.0	13.9	80.3	1.0	13.9	80.3
	'Nug' cake	1.7	32.0	70.8	1.0	32.0	70.8	3.4	32.0	70.8
	Oat vetch	1.1	20.9	74.0	–			–		
	Average		36.9	56.1		36.4	56.8		38.9	54.1
AEZ-2	Pasture	43.2	38.5	54.0	42.0	30.7	62.6	30.8	32.7	60.2
	Cut and carry grass	31.6	39.7	53.7	28.4	39.7	53.5	18.2	39.7	53.7
	Wheat straw	6.3	45.4	47.7	8.3	45.4	47.7	16.1	45.4	47.7
	Barley straw	2.1	47.1	46.4	2.6	47.2	46.4	5.5	47.8	45.9
	'Teff' straw	16.0	39.0	53.1	18.7	41.8	50.8	29.4	43.5	49.2
	Wheat bran	0.8	13.9	80.3	–			–		
	Average		39.4	53.4		37.0	56.2		40.0	53.0

Abbreviations: AEZ-1: upper highland semi-humid; AEZ-2: lower highland sub-humid to semi-humid; ADF: Acid detergent fiber; DMD = dry matter digestibility (DMD (g/100 g DM) = 83.58 – 0.824 * ADF (g/100 g M) + (2.626 * N (g/100 g DM)) (CSIRO, 2007).

The annual average EF ranged from 19 (calves) to 41 kg CH_4/-head/year (adult females) in the 'CSIRO' Tier 2 model, and from 19 (calves) to 59 kg CH_4/head/year (adult females) in the IPCC Tier 2 model. The IPCC Tier 2 model estimated considerably higher enteric CH_4 EFs for all cattle categories in both AEZs (Table 3). The Bland-Altman plot in Fig. 4 shows that the average difference between implied EFs estimated using the two Tier 2 methodologies was 17 kg CH_4/head/year (s.d. = 8.6), with the IPCC model estimating higher EFs on average (50 vs 33 kg CH_4/head/year). The IPCC methodology estimated a significantly higher implied GEI (104 vs 74 MJ/head/day). The Bland-Altman Plot in Fig. 5 for GEI indicates a mean difference of 29 MJ/head/day (s.d. = 18.6), which was significant ($P < 0.05$) in a one-sample t-test.

The results of the 'CSIRO' Tier 2 (Table 4) and IPCC Tier 2 models (Table 5) comparing the DMPs across seasons for different cattle categories reveal some differences in their findings. According to the CSIRO model, all adult females, intact males, castrates, heifers and young males exhibit the highest DMP during summer. However, for calves, the highest DMP is recorded in spring. The CSIRO model also highlights variations within different AEZs, with some categories showing similar patterns across AEZ-1 and AEZ-2, while others exhibit differences. In contrast, the IPCC model presents different seasonal patterns. It suggests that all adult females and intact males have the highest DMP during winter, while castrates show the highest DMP in winter or spring. Heifers and young males have the highest DMP during summer, while calves exhibit the highest DMP in spring. Similar to the 'CSIRO' model, the IPCC model also indicates variations within AEZ-1 and AEZ-2 for some cattle categories.

Author's point of view

The higher default Tier 1 EFs can be attributed to the greater default LWs compared to LWs measured in the present study. The mean LW of default Tier 1 (as stated in IPCC (2019)) and the present study (as measured in the field) were as follows: 356 vs 215 kg for adult females, 540 vs 235 kg for intact males, 540 vs

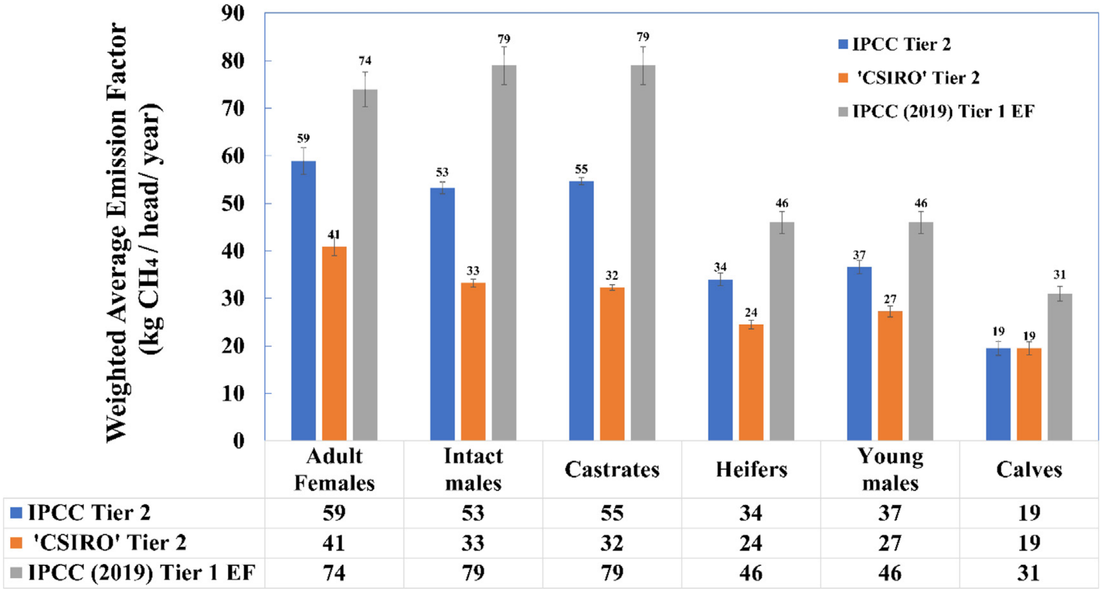

Fig. 2. Annual weighted enteric CH_4 emission factors (EFs) for cattle in smallholder systems estimated using IPCC and 'CSIRO' Tier 2 models, compared to IPCC 2019 Tier1 (2019) defaults. Error bars are expressed as ± 95% confidence interval. Abbreviations: IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization.

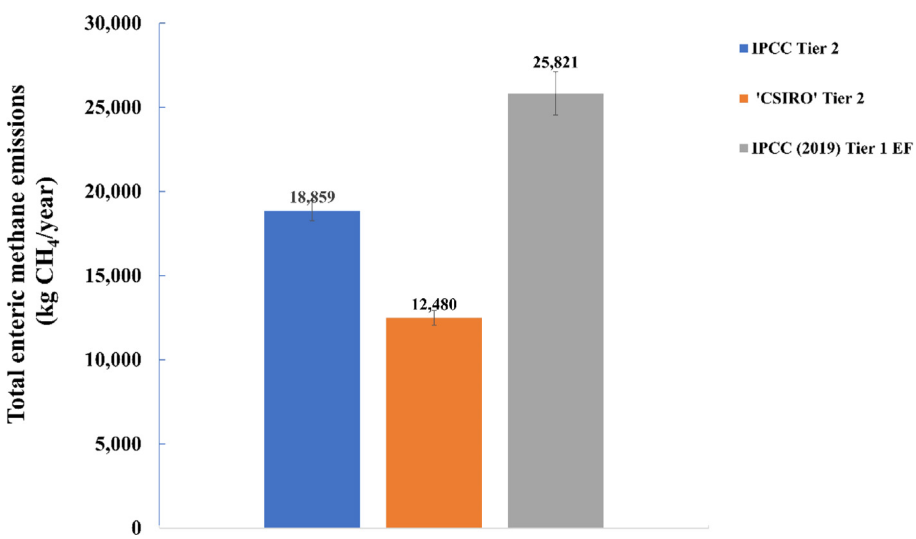

Fig. 3. Total enteric CH_4 emission (kg CH_4/year) for cattle in smallholder systems estimated using IPCC and 'CSIRO' Tier 2 models, compared to IPCC 2019 Tier1 (2019) defaults. Error bars are expressed as ± 95% confidence interval (n = 378). Abbreviations: IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization; EF: emission factor.

291 kg for castrates, 204 vs 140 kg for heifers, 204 vs144 kg for young males, and 82 vs 72 kg for calves, respectively. Considering that the predominant energy demands for the cattle categories in the present study were maintenance energy requirements (MER_m) using the 'CSIRO' model and net energy for maintenance (NE_m) using the IPCC model (Supplemental material: Table S2 and S3), it is expected that differences in EFs would correspond to differences in LW. In the case of adult females, apart from LW, milk yield plays a significant role in GEI for the IPCC Tier 2 method and DMI for the 'CSIRO' Tier 2 methods (Supplemental material: Table S2 and S3). The utilization of default Tier 1 EFs in smallholder mixed crop-livestock systems may result in an overestimation of emissions. This justifies the decision to avoid Tier 1 default value and instead utilize a Tier 2 method to minimize uncertainties associated with projected CH_4 emissions. This shift is crucial for enhancing the precision of emission assessments in smallholder mixed crop-livestock systems and reducing the likelihood of potential overestimations.

The variations in enteric CH_4 EFs between the two Tier 2 methods can be attributed to differences in GEI and Y_m, CH_4 conversion factor. The 'Y_m' back-calculated for the 'CSIRO' methodology averaged at 6.5%, which was lower than the value used by the IPCC model (7.0%). If 'Y_m' value was increased to 7.0%, the EF calculated by 'CSIRO' Tier 2 would rise by 7.7%, but the IPCC Tier 2 EF would still be 43% higher. Considering the default ± 20% uncertainty of IPCC Tier 2 enteric CH_4 EF for both methods, due to little documen-

Table 3
Estimated enteric CH_4 emission factors (kg CH_4 /head/year) using IPCC and 'CSIRO' Tier 2 models for different classes of cattle: (females >3 years, males (intact males and castrates) >3 years, heifers 1–3 years, young males 1–3 years and calves < 1 year) of North Shewa zone, Ethiopia.

Cattle category	AEZ	'CSIRO' Tier 2	IPCC Tier 2	*P-value*
Adult females	Overall	41[a]	59[b]	<0.001
	AEZ-1	42[a]	61[b]	<0.001
	AEZ-2	34[a]	48[b]	<0.015
Intact males	Overall	33[a]	53[b]	<0.001
	AEZ-1	34[a]	52[b]	<0.001
	AEZ-2	32[a]	55[b]	<0.001
Castrates	Overall	32[a]	55[b]	<0.001
	AEZ-1	33[a]	54[b]	<0.001
	AEZ-2	31[a]	55[b]	<0.001
Heifers	Overall	25[a]	34[b]	0.003
	AEZ-1	24[a]	33[b]	<0.001
	AEZ-2	27[a]	39[b]	<0.001
Young males	Overall	27[a]	37[b]	<0.001
	AEZ-1	28[a]	37[b]	<0.001
	AEZ-2	26[a]	37[b]	<0.001
Calves	Overall	19[a]	19[b]	<0.001
	AEZ-1	20[a]	20[b]	<0.001
	AEZ-2	18[a]	19[b]	<0.001

Abbreviations: AEZ-1: upper highland semi-humid; AEZ-2: lower highland sub-humid to semi-humid; IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization.
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$.

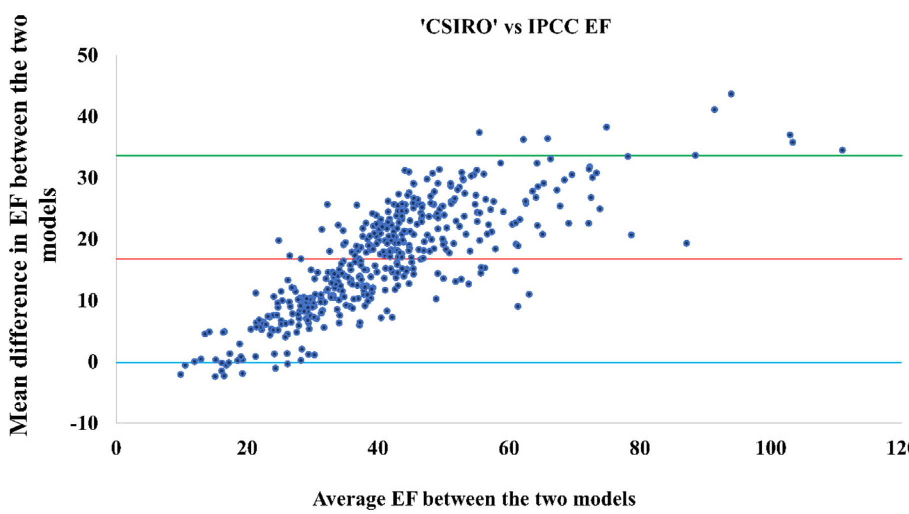

Fig. 4. Bland-Altman plot of mean difference in estimated implied EF for cattle in smallholder systems between IPCC and 'CSIRO' Tier 2 models and average EF (n = 378). Abbreviations: IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization; EF: emission factor.

tation of uncertainty for the 'CSIRO' Tier 2, the 'CSIRO' Tier 2 EF would still remain significantly lower than the IPCC Tier 2 EF. To account for model uncertainty, the differences between the models could be considered when estimating the uncertainty of EFs using the IPCC model. Thus, it appears that the disparity in GEI is the primary factor driving these differences.

The findings in the present study suggest that there would be discrepancies in the estimated enteric CH_4 emissions from cattle in the national GHG inventories if either Tier 2 method were to be applied. Therefore, it is challenging to recommend one method over the other without further experimentation using measured data from cattle. As stated by Jo et al. (2016), a model is effective within the specific range of data on which the model was developed. The equations provided in both methodologies were established based on experimental data conducted in Australia and other industrialized countries (CSIRO, 2007, Jo et al., 2016), which may not accurately reflect the cattle breeds and production systems found in Africa.

Overall, the 'CSIRO' model emphasizes summer as the season with the highest DMP for most cattle categories, while the IPCC model highlights winter as the peak season for adult females and intact males. The models also exhibit some similarities, such as both indicating spring as the season with the highest DMP for calves. These differences and similarities provide valuable insights into the seasonal patterns of methane production across different cattle categories. While the models used similar input parameters, the differences in equations and assumptions can lead to variations in the estimated EFs. Variations in the assumptions made about factors such as weight gain or loss can also contribute to inconsistencies.

The reproductive lifespan of cows varies due to several factors. Typically, cows are culled at an average age of 11 years or upon

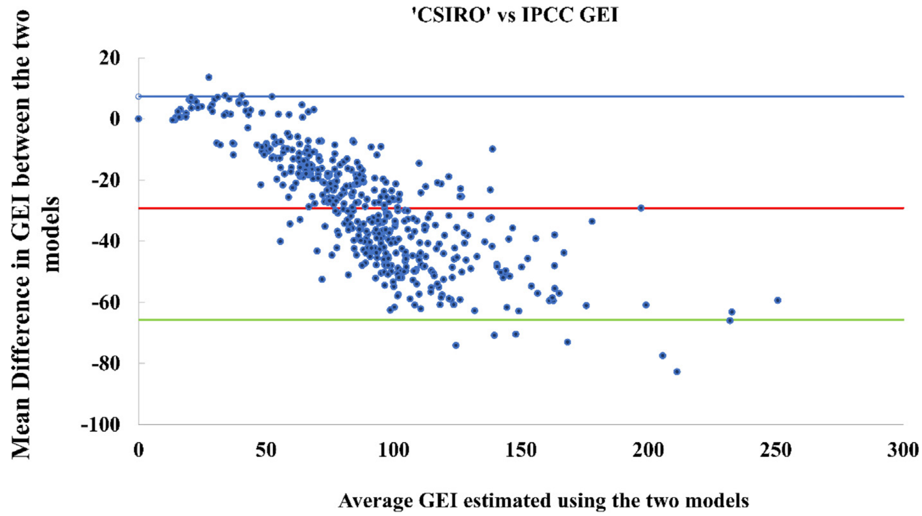

Fig. 5. Bland-Altman plot of mean difference in estimated implied GEI for cattle in smallholder systems between IPCC and 'CSIRO' Tier 2 models and average GEI (n = 378). Abbreviations: IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization; GEI: gross energy intake.

Table 4
Estimated daily enteric methane (g CH_4 / head/day)) using 'CSIRO' Tier 2 methodologies for different classes of cattle: (females >3 years, males (intact males and castrates) >3 years, heifers 1–3 years, young males 1–3 years, and calves < 1 year) of North Shewa zone, Ethiopia.

Category	AEZ	Spring	Summer	Winter	RMSE	*P-value*
Adult females	Overall	97[a]	125[b]	119[b]	3 025	<0.001
Intact males	Overall	88[a]	104[b]	83[a]	388	<0.001
Castrates	Overall	82[a]	103[b]	82[a]	280	<0.001
Heifers	Overall	60[a]	79[b]	64[a]	231	<0.001
Young males	Overall	69[a]	86[b]	71[a]	408	<0.001
Calves	Overall	63[a]	48[b]	46[b]	214	0.010
Adult females	AEZ-1	100[a]	128[b]	124[b]	3 045	0.001
	AEZ-2	78[a]	111[a]	97[a]	2 659	0.185
Intact males	AEZ-1	89[a]	104[b]	84[a]	404	<0.001
	AEZ-2	78[a]	105[b]	81[a]	289	<0.001
Castrates	AEZ-1	84[a]	103[b]	83[a]	307	<0.001
	AEZ-2	74[a]	104[b]	79[a]	166	<0.001
Heifers	AEZ-1	61[a]	75[b]	64[a]	212	<0.001
	AEZ-2	54[a]	102[b]	65[a]	167	<0.001
Young males	AEZ-1	69[a]	88[b]	73[a]	366	<0.001
	AEZ-2	70[a]	80[a]	64[a]	585	0.404
Calves	AEZ-1	66[a]	47[b]	46[b]	226	0.006
	AEZ-2	49[a]	55[a]	44[a]	67	0.489

Abbreviations: AEZ-1: upper highland semi-humid; AEZ-2: lower highland sub-humid to semi-humid; IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$.

reaching a parity of 5. At this point, they are either sold or slaughtered directly at the farm. The cows typically have a lactation period of approximately 305 days. Regarding the fate of calves, they are usually not slaughtered for beef purposes. Instead, farmers often choose to sell them at different stages of their growth as an additional source of income or retain them on the farm until they reach reproductive maturity. While some calves may be marketed for beef, their primary purpose is not solely for beef production. In Ethiopia, the weight at which cattle are typically slaughtered for beef can vary. According to Shapiro et al. (2017), the average slaughter weights range from 240 to 255 kg. These figures provide insight into the average weights at which cattle are marketed for beef and can be useful for evaluating enteric emissions in the context of beef production.

Since both models estimate GEI, it is challenging to determine which model is more accurate or closer to the actual intake. To evaluate the accuracy of predicted intakes and emissions from the models, it is necessary to compare them with actual intakes and emissions using experimental data. This empirical comparison will enable us to determine which model more accurately predicts both GEI and EFs. By validating the models against real-world data, we can gain insights into their performance and identify any potential discrepancies or areas for improvement.

Ethics approval

Ethical approval was obtained from ILRI Institutional Research Ethics Committee (ILRI-IREC2019-11, ILRI-IREC2019-11/1 and IACUC2019-34).

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChaptGPT-GPT4 in order to improve the language and readability

Table 5
Estimated daily enteric methane (g CH_4 / head/day)) using IPCC Tier 2 methodologies for different classes of cattle: (females >3 years, males (intact males and castrates) >3 years, heifers 1–3 years, young males 1–3 years, and calves < 1 year) of North Shewa zone, Ethiopia.

Category	AEZ	Spring	Summer	Winter	RMSE	*P-value*
Adult females	Overall	150[a]	159[a]	178[b]	6 352	0.035
Intact males	Overall	156[a]	129[b]	149[a]	803	<0.001
Castrates	Overall	154[a]	135[b]	159[a]	358	<0.001
Heifers	Overall	84[a]	104[b]	94[a]	579	0.001
Young males	Overall	92[a]	108[b]	104[b]	651	0.013
Calves	Overall	64[a]	44[b]	48[b]	231	0.004
Adult females	AEZ-1	154[a]	167[a]	184[b]	6 363	0.046
	AEZ-2	124[a]	123[a]	151[a]	5 509	0.473
Intact males	AEZ-1	155[a]	129[b]	147[a]	881	<0.001
	AEZ-2	162[a]	133[b]	155[a]	428	0.004
Castrates	AEZ-1	152[a]	136[b]	159[a]	391	<0.001
	AEZ-2	160[a]	132[b]	159[a]	234	<0.001
Heifers	AEZ-1	84[a]	99[b]	93[a]	503	0.022
	AEZ-2	89[a]	146[b]	97[a]	555	0.009
Young males	AEZ-1	90[a]	108[b]	106[b]	588	0.006
	AEZ-2	98[a]	105[a]	98[a]	941	0.849
Calves	AEZ-1	67[a]	43[b]	47[b]	246	0.003
	AEZ-2	52[a]	51[a]	54[a]	85	0.960

Abbreviations: AEZ-1: upper highland semi-humid; AEZ-2: lower highland sub-humid to semi-humid; IPCC: Intergovernmental Panel on Climate Change; CSIRO: Commonwealth Scientific and Industrial Research Organization
[a,b] Values within a row with different superscripts differ significantly at $P < 0.05$.

of their work. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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CA, SML, SM, LM and **MWG**: Conceptualization, Methodology; **JGK**: Resources; **DGM, JGK, DGM** and **TW**: Investigation; **PWN**: curation; **PWN** and **EBG**: data analysis; **EBG**: writing original draft; **AW, SM, MWG, PN, CA**: reviewing; **CA**: supervision, project administration.

Declaration of interest

None

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