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Comparison of methodologies for estimating enteric methane emission factors from sheep in smallholder systems in Africa: A case study from Ethiopia

Endale B. Gurmu [a], Phyllis W. Ndung'u [b], Andreas Wilkes [c], Daniel Getahun [d], Michael W. Graham [b], Sonja M. Leitner [b], Svenja Marquardt [b], Daniel G. Mulat [b], Lutz Merbold [e], Tigist Worku [f], Jesse K. Gakige [b], Dereje Tadesse [d], Mekete Bekele [d], Claudia Arndt [b,*]

[a] *Mekelle University, College of Veterinary Sciences, Ethiopia*
[b] *Mazingira Centre for Environmental Research and Education, International Livestock Research Institute (ILRI), Naivasha Rd, Nairobi 00100, Kenya*
[c] *New Zealand Agricultural Greenhouse Gas Research Centre (NZAGRC), New Zealand*
[d] *Debre Berhan University, Department of Animal Production, Ethiopia*
[e] *Integrative Agroecology Group, Research Division Agroecology and Environment, Agroscope, Reckenholzstrasse 191, Zurich 8046, Switzerland*
[f] *International Livestock Research Institute (ILRI), Ethiopia*

A R T I C L E I N F O

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A B S T R A C T

In Ethiopia, enteric methane emissions from sheep contribute around 7 % to the national greenhouse gas (GHG) budget. This study examined the gross energy intake (GEI) and enteric methane emission factors (EFs) of sheep in smallholder systems in North Shewa, Ethiopia, using locally derived data via household surveys. The surveys encompassed two agroecological zones (AEZs) and analyzed various sheep classes across seasons. The study followed the Commonwealth Scientific Industrial Research Organization (CSIRO) Tier 2 methodology, which had previously been used in Kenya, and compared the results with those derived from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Tier 2) methodology. The EFs from the two Tier 2 methodologies were compared with IPCC default Tier 1 EF. The ranges of GEI and EF estimated for the different sheep classes showed similarity with larger variations observed for IPCC Tier 2 estimates. The estimated GEI for the various sheep classes ranged from 11.1 to 13.8 MJ day^{-1} ('CSIRO' Tier 2) and 10.2–14.7 MJ day^{-1} (IPCC Tier 2). The estimated EFs ranged from 4.8 to 5.9 kg CH_4 animal^{-1} year^{-1} ('CSIRO' Tier 2) and 4.5–6.5 kg CH_4 animal^{-1} year^{-1} (IPCC Tier 2). The flock-level EF was computed by aggregating the EFs of the different sheep categories. The flock level EF estimated by the IPCC Tier 2 (6.0 $\pm$ 0.1 kg CH_4 animal^{-1} year^{-1}) was significantly higher compared to both the 'CSIRO' Tier 2 and IPCC Tier 1 methods. Based on the findings, we can say that variations in EF values emphasize the significance of taking different Tier 2 approaches into account when evaluating and comparing CH_4 emissions estimates in smallholder sheep farming systems. However, there is a need for further investigations to compare the two Tier 2 methodologies against actual intake and emission measurements to decide which methodology is better.

1. Introduction

Ethiopia is home to a substantial small ruminant population, with approximately 40 million sheep and 51 million goats (CSA, 2020). These animals play a crucial role in the livelihoods of livestock keepers and contribute to food security, income generation, and various socio-cultural functions (Wodajo et al., 2020; Jemberu et al., 2022). Small ruminants exhibit greater resilience compared to cattle, thereby increasing their importance in light of climate change (Government of Ethiopia, 2021).

For effective mitigation of greenhouse gas emissions (GHG) of small ruminant farming, reliable data on enteric CH_4 emissions is essential (Goopy et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) guidelines recommend specific methodologies, such as the Tier 2 method, for estimating enteric CH_4 production. This approach calculates CH_4 EFs (kg CH_4 animal^{-1} year^{-1}) by considering the methane

* Corresponding author.
E-mail address: Claudia.Arndt@cgiar.org (C. Arndt).

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conversion factor (Ym)-the fraction of an animal's gross energy intake converted to methane and the daily gross energy intake (GEI) (Jo et al., 2016). Previous studies by Wilkes et al. (2020) and Goopy et al. (2021) highlight the value of using country-specific livestock data for emission estimates. They found that Tier 2 methodology reduced uncertainties associated with sheep EFs compared to the IPCC default Tier 1 values, leading to more accurate results.

Despite the significant small ruminant population in Africa, research on their climate impact remains limited. Existing research has primarily focused on cattle, with limited attention given to small ruminants. Sheep, constituting 26 % of Ethiopia's ruminant population (CSA, 2020), accounted for 7 % of the 3,672Gg enteric CH_4 emissions from ruminant livestock in Ethiopia in 2018 (Wilkes et al., 2020). This study emphasized the importance of representative sample surveys across production systems to gather more precise activity data and EFs for enhancing national greenhouse gas inventories. So far, no attempt has been made to estimate enteric CH_4 emission of sheep using methods other than the IPCC methods. In Kenyan smallholder systems, alternative Tier 2 methodologies, such as the Commonwealth Scientific Industrial Research Organization ('CSIRO') Tier 2 methodology, have been employed to estimate CH_4 emissions from small ruminants (Goopy et al., 2021). As opposed to IPCC which estimates intake based on net energy, this method estimates intake based on metabolizable energy. While the IPCC Tier 2 method estimates EF from GEI, the 'CSIRO' Tier 2 method estimates EF from dry matter intake (DMI) (Ndung'u et al., 2020). Given the similarities between grazing systems in Australia, for which the 'CSIRO' Tier 2 equations were developed (Jones, 2010), and smallholder systems in Africa, it is worth considering the applicability of the 'CSIRO' Tier 2 equations for estimating enteric CH_4 emissions in sheep within smallholder systems in Ethiopia.

We hypothesized that the two Tier 2 methodologies will produce different results, and there will also be significant differences between Tier 2 and Tier 1 values. The objectives of the current study were to compare models for estimating enteric CH_4 EF of sheep. Animal and feed characteristics specific data were obtained from the field survey, and EF for enteric fermentation was estimated using IPCC Tier 1, 'CSIRO' Tier 2, and IPCC Tier 2 methods. Specifically, we aimed to predict the enteric CH_4 EF for sheep using the 'CSIRO' Tier 2 methodology and compare the results with EF estimates derived from the IPCC Tier 2 method and the default IPCC Tier 1 EF. Through the comparison of results, it is possible to assess the applicability of different methodologies for estimating sheep enteric CH_4 emissions in the specific context of Ethiopia. This knowledge can guide policymakers in selecting the most appropriate methodology for inclusion in national greenhouse gas inventories.

2. Material and methods

2.1. Study site

This study was undertaken from February 2020 to January 2021 in the North Shewa zone, which is an administrative zone located in the Amhara Regional State of Ethiopia. This region is characterized by uneven and rugged mountainous highlands in the northern and central parts of the zone, while the periphery consists of extensive plains and deep gorge sand cliffs (Abegaz and Mekoya, 2020). The landscape in this area exhibits variations in climate, soil type, vegetation, and livestock management, although mixed crop-livestock systems are predominant (Shefine, 2018). The North Shewa zone experiences three distinct seasons. The first is the summer/'Kiremt' season, which is the long rainy season occurring from June to September. During this season, the rainfall ranges between 633 and 1071 mm. The second season is winter/'Bega,' which is the dry season from October to January, with rainfall ranging from 25 and 209 mm. The third season is spring/'Belg,' the short rainy season lasting from February to May, with rainfall varying between 121 and 484 mm (Romilly and Gebremichael, 2011).

The household selection for data collection involved several criteria, including the use of GPS points and additional considerations. A total of 33 GPS points were randomly chosen from two different agroecological zones (AEZs): the upper highland sub-humid to semi-humid zone (AEZ-UH) and the lower highland sub-humid to semi-humid zone (AEZ-LH). These GPS points served as reference locations for selecting households within each zone. AEZ-UH is characterized by an elevation range of 2438 to 3048 m above sea level (m.a.s.l), temperatures ranging from 10 to 15 degrees Celsius (°C), and an annual rainfall of 1200 to 1500 mm. AEZ-LH, on the other hand, is characterized by an elevation range of 1829 to 2438 m.a.s.l, temperatures ranging from 15 to 18 (°C), and an annual rainfall of 1200 to 1500 mm (Sombroek et al., 1982; Macharia, 2004). In addition to the agroecological zone selection, other criteria were considered during the household selection process. During the initial household visits, the selection process involved obtaining consent from farmers to participate in the study. Additionally, the possession of sheep by the households was a criterion for selection, as the study focused on farming systems involving these animals. All sheep in the households were included in the study regardless of their breed. A total of 77 households were considered based on the aforementioned criteria. The households were visited four times over the course of one year, at the beginning of the study (February 2020) and then at the end of each of the three seasons.

Farmers in the study area primarily rely on mixed agriculture, growing cereal crops like barley, wheat, and 'teff' (*Eragrostis tef*), alongside pulse crops such as Faba bean and field pea (Hilemelekot et al., 2021). These crops are widely grown by farmers in the region. Sheep are primarily kept at pasture and graze for most of the day, typically from 0800 to 1700 hours. They graze in various locations, including around the homesteads, roadsides, and communal grazing sites. Additionally, after the harvest of crops, sheep are allowed to graze on the remaining stubble in the fields. This practice helps to utilize the crop residues efficiently. Apart from grazing, a cut-and-carry feeding system is also practiced by around 45 % of households, particularly during the evening. In this system, farmers cut the grass, forage, or other supplementary feed resources and carry them to feed the sheep.

2.2. Input data collection

Data relevant to sheep activity, diet, and performance were collected by conducting household visits, following the protocol established by Goopy et al. (2021). During the initial visits to the participating households, all sheep were tagged with ear tags (Allflex Europe SA, Vitre, France) for identification purposes.

Sheep ages were determined through a combination of dentition analysis following the method described by Torell et al. (1998) and information provided by the farmers. The animals were categorized into six distinct classes based on their age, sex, and physiological condition. These classes included juveniles (≤ 6 months old), young females (6–12 months old), young males (6–12 months old), intact rams (> 12 months old), castrated rams (> 12 months old), and mature ewes (> 12 months old). At each household visit, the ages, and classes of the study animals were revised, and the corresponding animal numbers for each class were adjusted accordingly. Furthermore, the newborn lambs identified during subsequent household visits were included in the study. Class adjustments were implemented for rams previously identified as intact but found to be castrated during subsequent household visits.

Live weight was measured using a portable animal-weighing scale (EKW Endeavour Instrument Africa Ltd., Nairobi, Kenya). Average LW by animal category was then calculated for each season. Live weight change (LWC) was calculated by subtracting the live weight at the end of the season from the live weight at the start of the season. Time consistency and order of households were maintained when weighing animals throughout the study period. The optimal time to weigh the animals was in the morning before they were fed or released for grazing from barns.

The parity (number of previous lambing) and physiological condition (pregnant or lactating) of the sheep were determined through a combination of farmers' information and direct observations.

The 'CSIRO' Tier 2 methodology incorporates the measurement of the average daily distance covered by grazing animals. To obtain this data, GPS collars were attached to 10 sheep from the six categories for a continuous period of 24 hours over three consecutive days, as outlined in Allan et al. (2013). Juveniles were not taken into account as they were predominantly kept near the homestead while the remaining sheep grazed.

In the study region, sheep are not milked by farmers; therefore, milk production or milk yield (MY) was assumed to be equivalent to daily milk consumption (DMC) of pre-ruminant lambs (≤3 months). The following equation, based on Radostits and Bell (1970) was utilized to calculate DMC.

$$DMC = MLW * 0.107 + 3.39 * LWG \quad (1)$$

where, DMC (l day^{-1}) represents the daily milk consumption of pre-ruminant lambs; MLW (kg) corresponds to the lamb's mean live weight; 0.107 (l kg^{-1}) denotes the amount of milk required for maintenance per kilogram of lamb live weight; 3.39 (l kg^{-1}) represents the additional amount of milk needed per kilogram of live weight gain, and LWG (kg day^{-1}) indicates the LW gain of the lamb per day.

The feed basket refers to the specific combination of different types of feed provided to the sheep. It was determined by considering the individual ingredients that constitute the sheep's diet. The feed basket information was collected from representative households. For AEZ-UH, 30 households were selected, while for AEZ-LH, 5 households were selected. The selection of households was based on expert judgment, considering those households most likely to provide meaningful and representative data. To determine the proportion of each feedstuff in the total diet, the method described in Marquardt et al. (2020) and Goopy et al. (2021) was followed. In short, a list of various feed items was compiled and the proportions of each feed item, on a DM basis, about the total feed availability for the corresponding season was determined. These proportions, specific to each season, indicate the contribution of each feed item to the overall seasonal feed basket.

Feed samples that form part of the seasonal feed basket were collected. The fresh weight and air-dried weight of the samples were recorded. At the laboratory, air-dried feed samples were air-forced in an oven set at 60°C for 24 hours. The samples were then weighed to get the analytical DM. Subsequently, the samples were then ground through a hammer mill fitted with a 1-mm sieve. Samples of the different feedstuffs were analyzed at the Mazingira Lab, ILRI, Nairobi. The analysis included measurements of gross energy (GE; MJ kg^{-1} DM), dry matter (DM; ISO, 6496 (1999)), total nitrogen (N; AOAC (2006), Method 990.3), and acid detergent fiber (ADF; Van Soest et al. (1991)).

The dry matter digestibility (DMD) of individual feedstuffs was determined using the equation developed by Oddy et al. (1983):

$$DMD = 83.58 - 0.824 * ADF + (2.626 * N) \quad (2)$$

where DMD represents the DMD in grams per 100 g of dry matter; The constants 83.58 and 0.824 were derived from the study by Oddy et al. (1983); ADF refers to the acid detergent fiber content in grams per 100 g of dry matter, and N represents the nitrogen content in grams per 100 g of dry matter.

The seasonal mean DMD (SM-DMD) per AEZ was calculated using the following equation, as described by Goopy et al. (2021):

$$SM-DMD = \sum \frac{(\%\text{diet of individual feedstuff} + \text{DMD of the individual feedstuff})}{100} \quad (3)$$

where, SM-DMD (%) represents the seasonal mean DMD of the animal diet, expressed as a percentage; "% diet of individual feedstuff" refers to the percentage contribution of each feedstuff, on a DM basis, in the respective seasonal feed basket; and "% DMD of the feedstuff" denotes the DMD of each feedstuff, as determined by the equation mentioned earlier (Eq.2). By applying this equation, the SM-DMD can be calculated by summing the products of the percentage contribution of each feedstuff and its corresponding DMD, divided by 100. This provides an estimation of the average DMD of the animal diet for each season in the specific AEZ.

To calculate EFs using the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Tier 2 methodology), the SM-DMD must be converted to feed digestibility (DE %) using the following equation from CSIRO (2007).

$$DE = \frac{DMD * 0.172 - 1.707}{0.81 * GE} * 100 \quad (4)$$

where, DE represents the portion of gross energy (GE) in the feed that is not excreted in the feces, expressed as a percentage. (0.172 * DMD - 1.707) represents the metabolizable energy content of the diet; The factor 0.81 is used to convert metabolizable energy to DE; and GE refers to the gross energy content of the animal feed, measured in megajoules per kilogram of dry matter (MJ kg^{-1} DM).

2.3. Estimation of enteric CH_4 using the 'CSIRO' Tier 2 method

The 'CSIRO' Tier 2 method estimates enteric EF using equations derived from CSIRO (2007) and described in Goopy et al. (2021). It calculates the daily enteric CH_4 production (DMP) by estimating daily DMI using the following equations (Charmley et al., 2016).

$$DMI = \frac{MER_{Total}}{GE * \left(\frac{SMDMD}{100}\right) * 0.81} \quad (5)$$

where, DMI (kg day^{-1}) represents the dry matter intake of the animal. MER_{Total} (MJ day^{-1}) is the sum of all maintenance energy requirements, including maintenance, locomotion, growth, and lactation. GE (MJ kg^{-1} DM) refers to the gross energy concentration of the diet for each season. SMDMD (%) represents the seasonal dry matter digestibility. A detailed description of the equations to estimate MER_{Total} using the 'CSIRO' Tier 2 methodology is presented in Supplementary material (SM-1).

The DMP is calculated using Eq. 6 based on Charmley et al. (2016):

$$DMP = 20.7 * DMI \quad (6)$$

where, DMP (g day^{-1}) represents the daily methane production of an individual animal. It is obtained by multiplying the DMI (kg day^{-1}) by a constant factor of 20.7 (g of CH_4 kg^{-1} DMI).

2.4. Estimation of enteric CH_4 using the IPCC Tier 2 method

A detailed description of the equations to estimate enteric EF using the IPCC Tier 2 methodology is presented in IPCC (2019) guidelines. It calculates the DMP by estimating daily GEI using the following equations.

$$GEI = \left[\frac{\left(\frac{NE_M + NE_A + NE_L + NE_P}{REM} \right) + \left(\frac{NE_G}{REG} \right)}{DE/100} \right] \quad (7)$$

where, GEI (MJ day^{-1}) represents the gross energy intake of the sheep; NE_M (MJ day^{-1}) is the net energy required by the sheep for maintenance; NE_A (MJ day^{-1}) denotes net energy for animal activity; NE_L (MJ day^{-1}) represents net energy for lactation; NE_P (MJ day^{-1}) stands for net energy required for pregnancy; NE_G (MJ day^{-1}) denotes net energy needed for growth. REM is the ratio of net energy available in the diet for maintenance to digestible energy consumed, and REG represents the ratio of net energy available for growth in the diet to digestible energy consumed; DE is digestible energy expressed as a percentage of gross energy. The net energy for wool production was not considered. The farmers may shear the fleece of their sheep for personal use, without keeping track of the quantity of wool produced annually. As a result, these farmers do not have accurate information regarding the amount of wool generated by their sheep each year.

The DMP is calculated using equations derived from IPCC (2019) guidelines as follows

$$DMP = \left[\frac{\left(GEI * \frac{Y_m}{100} \right)}{55.65} * 1000 \right] \quad (8)$$

where, DMP represents the daily CH_4 production (g CH_4 day^{-1}); GEI (MJ day^{-1}) is the gross energy intake, and Y_m (%) is the CH_4 conversion rate, which is the fraction of GEI in the form of feed that is converted to CH_4. The present study used the Y_m values proposed in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for small ruminants (6.7 %, IPCC (2019), Table 10.13 (Updated)). When implementing the IPCC equations on a seasonal basis, NE_G was calculated using LW gain (WG_{lamb}, kg day^{-1}) and the LW (kg) at the start and end of the respective seasons ($LW_i + LW_f$). In cases where animals experienced weight loss, it was assumed that there was zero weight gain during that period.

3. Comparison of results from the models

The 'CSIRO' Tier 2, IPCC Tier 2, and IPCC Tier 1 were used to estimate enteric EFs for sheep. For Tier 1, the default EF for sheep in low-productivity systems, as specified in the IPCC (2019) guidelines (Table 10.10, updated) were employed. This default value is similar across all sheep classes.

The Tier 2 models were implemented in Microsoft Excel to estimate DMP per season and sheep class. The 'CSIRO' Tier 2 method was used to estimate DMI, while the IPCC Tier 2 method was used to estimate GEI. These inputs were then used to estimate DMP for each season. The mean of DMP values (g CH_4 day^{-1}) for the three seasons was converted to kg CH_4 day^{-1} and multiplied by 365 to obtain the annual EF (kg CH_4 animal^{-1} year^{-1}).

For comparison purposes between the two models, the DMI estimated using the 'CSIRO' Tier 2 method was converted to GEI by dividing DMI by the GE concentration of the diet.

The overall EFs from all sheep in the study area, referred to as flock-level EFs, were computed for both Tier 2 models. The results were presented as mean ± SE, where the standard error (SE) is determined by dividing the standard deviation of the observations by the square root of the number of observations.

The estimated values from Tier 2 methods were compared with each other and the IPCC Tier 1 default EF value using error bars.

To mitigate potential biases arising from the significant disparity in sheep class populations between AEZ-UH and AEZ-LH (as indicated in Table 1), the EF and GEI results were not segregated by AEZ. Segregating the results by AEZ could have led to unreliable or skewed outcomes. AEZ-LH does not include sufficient numbers of a diverse range of sheep classes. This inadequate representation could lead to skewed or biased outcomes if the results were segregated based on AEZ. Therefore, the EF results were reported by combining sheep from both AEZs.

Table 1
Flock structure, by animal class and topographic zone, over the 12-month survey period in the study region in the North Shewa zone of Ethiopia.

Topographic zone	Animal class	Season		
		Spring	Summer	Winter
		Head of sheep		
AEZ-UH	Juveniles (<6 months old)	65	71	70
	Young males (6–12 months old)	17	15	20
	Young females (6–12 months old)	17	12	15
	Intact rams (>12 months old)	53	43	41
	Castrated rams (>12 months old)	10	15	17
	Mature ewes (>12 months old)	176	182	169
	Total	338	338	332
AEZ-LH	Juveniles (<6 months old)	3	6	5
	Young males (6–12 months old)	3	1	-
	Young females (6–12 months old)	4	-	-
	Intact rams (> 12 months old)	8	5	6
	Castrated rams (> 12 months old)	1	3	3
	Mature ewes (> 12 months old)	19	21	19
	Total	38	36	33
Sum study region	Juveniles (<6 months old)	68	77	75
	Young males (6–12 months old)	20	16	20
	Young females (6–12 months old)	21	12	15
	Intact rams (> 12 months old)	61	48	47
	Castrated rams (> 12 months old)	11	18	20
	Mature ewes (> 12 months old)	195	203	188
	Total	376	374	365

AEZ: Agroecological zone; AEZ-UH: upper highland semi-humid; AEZ-LH: lower highland sub-humid to semi-humid

4. Results

According to the survey findings, there was observed variation in sheep populations across different seasons. The total number of sheep, including all classes, ranged from 365 to 376 in the two surveyed AEZs (Table 1). The number of sheep per household ranged from 1 to 13, with an average of 6 sheep per household. As shown in Table 1, around 90 % of the sheep are in AEZ-UH. The number of mature ewes was

Table 2
Seasonal mean live weights (kg) of the animal classes of sheep in the two agroecological zones in the North Shewa zone of Ethiopia.

Animal class	Season		
	Spring	Summer	Winter
	Mean live weight (SE)		
Juveniles (<6 months old)	12.0 (0.5)	10.8 (0.5)	11.0 (0.7)
Young males (6–12 months old)	18.5 (0.8)	20.4 (0.9)	22.9 (0.7)
Young females (6–12 months old)	17.7 (0.4)	19.6 (1.2)	22.2 (0.7)
Intact rams (> 12 months old)	27.0 (0.8)	26.0 (0.6)	27.5 (0.6)
Castrated rams (> 12 months old)	29.3 (1.3)	32.6 (0.9)	32.7 (1.0)
Mature ewes (> 12 months old)	25.4 (0.3)	25.4 (0.2)	26.8 (0.3)

Values in parenthesis are standard error (SE) of mean substantially higher compared to the other classes. Numbers of the different classes of sheep varied across seasons due to the combined effects of births, deaths, sales, and purchases.

Table 2 presents the LW of various sheep classes in the study area. The seasonal trends differ for different sheep classes. Juveniles exhibit a slight decrease from spring to summer, followed by a slight increase towards winter. Young males and young females generally showed an increasing trend from spring to summer, with further increases observed in winter. Intact rams and mature ewes remained relatively stable throughout the seasons. Castrated rams, on the other hand, demonstrated an upward trend from spring to summer, followed by a consistent level of stability from summer to winter. This shift in data can be attributed to the reclassification of rams that were initially labeled as 'intact' but were found to be castrated during subsequent visits.

Apart from the juveniles, all other sheep classes were observed to travel an average distance of 2.2 kilometers each day across all seasons.

The seasonal feed basket (Table 3) showed modest variations in the digestibility of different feedstuffs across seasons. The average SM-DMD remained relatively consistent across the seasons.

Table 4 presents an estimate of GEI and enteric CH_4 EFs for different categories of sheep in the North Shewa zone, Ethiopia. The values shown in the table exhibit variations across animal classes and between the two Tier 2 estimation methods. Using the 'CSIRO' Tier 2 method, the estimated GEI ranged from 11.1 MJ day^{-1} for juveniles to 13.8 MJ day^{-1} for intact rams. On the other hand, employing the IPCC Tier 2 method, the estimated GEI ranged from 10.2 MJ day^{-1} for juveniles to 14.7 MJ day^{-1}. Regarding the estimated EFs, the table demonstrates that using the 'CSIRO' Tier 2 method, the EFs ranged from 4.8 to 5.9 kg CH_4 $animal^{-1}$ $year^{-1}$. Meanwhile, employing the IPCC Tier 2 method, the EFs varied from 4.5 to 6.5 kg CH_4 $animal^{-1}$ $year^{-1}$.

Fig. 2 illustrates a comparison of the estimated Tier 2 flock-level EFs for sheep in North Shewa, Ethiopia, with the IPCC Tier 1 default EF. The figure indicates that the estimated flock-level EF obtained through the 'CSIRO' Tier 2 approach (5.3 ± 0.1 kg CH_4 $animal^{-1}$ $year^{-1}$) was not significantly different from the IPCC Tier default EF value of 5.0 kg CH_4 $year^{-1}$. However, the estimated flock-level EF obtained through the IPCC Tier 2 method (6.0 ± 0.1 kg CH_4 $animal^{-1}$ $year^{-1}$) was significantly higher than both the 'CSIRO' Tier 2 and IPCC Tier 1 default values.

5. Discussion

The findings of this study provide valuable insights into the estimation of intake and enteric CH_4 EFs for sheep in smallholder systems in Africa, specifically in the case study from Ethiopia. The results demonstrate the importance of considering various sheep classes and their seasonal variations when estimating these factors. By examining the population dynamics of sheep, it was observed that the number of mature ewes was significantly higher compared to other classes, indicating their prominence in smallholder systems. This aligns with the findings of Alilo (2019), who highlighted the crucial role of mature ewes in sustaining and expanding sheep populations in similar agricultural contexts.

The seasonal trends in LW among different sheep classes have important implications for understanding their growth patterns and feed requirements. The slight decrease in LW of juveniles in the long rainy season (summer) could be associated with their susceptibility to cold stress as they have less fat (Mota-Rojas et al., 2022). Simeonov et al. (2022) investigated the impact of varying environmental temperatures, including medium (12.6 °C), low (5.1 °C), and very low (−3 °C) settings, and found that lambs reared at an average temperature of 12.6 °C exhibited significantly greater weight gain compared to those raised at lower temperatures. According to Ethiopia's National Meteorological Agency's annual Climate bulletin, temperature values as low as the freezing point (0°C) were recorded at the current study location.

Conversely, the increasing trend observed in young males and females during the same period suggests favorable conditions for their growth. The stability of live weight in intact rams and mature ewes throughout the seasons may indicate their ability to maintain consistent body weight and productivity, which is crucial for reproductive success and overall flock performance (Leng, 2014). It is important to note that these observations are derived from overall average LW and may mask the variations in LW exhibited by individual animals across seasons.

The modest fluctuations in feedstuff digestibility across seasons mirror the changes in forage quality attributed to distinct seasonal growth stages. However, the digestibility was consistent across seasons which exhibit the availability of relatively stable feed resources. The significant difference in sample size of animals and feeds between the two AEZs limits the ability to compare findings between the two zones. These findings are consistent with studies highlighting the influence of

Table 3
Composition of seasonal diets and dry matter digestibility (DMD) in the study region in the North Shewa zone of Ethiopia.

	Feedstuff	Spring				Summer				Winter			
		% diet	CP (% of DM)	ADF (% DM)	% DMD[2]	% diet	CP (% of DM)	ADF (% DM)	% DMD[2]	% diet	CP (% of DM)	ADF (% DM)	% DMD[2]
AEZ-UH	Teff Stover	10.6	3.9	39.0	53.1	7.4	4.2	48.9	45.1	12.4	3.9	39.0	53.1
	Barley Stover	9.3	3.8	46.5	46.9	8.8	4.1	48.4	45.4	15	4.0	47.7	46.0
	Wheat Stover	12.3	4.2	48.6	45.3	7.8	4.2	48.9	45.1	12.5	3.5	43.4	47.7
	Pasture grass	58.6	7.5	33.8	58.9	65.5	8.1	33.8	59.1	52.3	5.7	36.0	56.3
	Cut & and carry grass	7.7	5.1	39.9	52.8	9	5.4	38.9	53.7	7.8	5.3	40.1	52.7
	Legume	1.5	32.4	32.0	74	-			-	-			-
	Pea residue	-			-	1.5	5.6	45.0	48.8	-			-
	Average				55.2				55.2				53
AEZ-LH	Teff Stover	15.9	3.9	39.0	53.1	18.3	3.9	41.8	50.8	31.9	3.5	44.1	48.7
	Barley Stover	1.6	3.8	47.1	46.4	2.0	3.8	46.7	46.7	4.0	4.0	47.8	45.9
	Wheat Stover	5.9	3.5	45.4	47.7	6.0	3.5	45.4	47.7	12.0	3.5	45.4	47.7
	Pasture grass	38.5	5.3	36.9	55.4	39.6	6.6	34.1	58.2	29.6	9.9	30.0	62.8
	Cut and carry grass	36.6	6.7	39.7	53.7	34.1	6.7	39.7	53.7	22.5	6.7	39.7	53.7
	Wheat bran	1.5	19.3	13.9	80.3	-			-	-			-
	Average				54.2				54.5				53.8

AEZ: Agroecological zone; AEZ-UH: upper highland semi-humid; AEZ-LH: lower highland sub-humid to semi-humid. CP: Crude protein (CP= Nitrogen (N) content x 6.25); ADF: Acid detergent fiber.

Table 4
Estimated gross energy intake (GEI) and the enteric CH_4 emission factors (EF) for different sub-categories of sheep across the two agroecological zones in the North Shewa zone, Ethiopia.

Animal class	'CSIRO' Tier 2		IPCC Tier 2		IPCC Tier 1
	GEI (MJ day^{-1})	EF (kg CH_4 animal^{-1}year^{-1})	GEI (MJ day^{-1})	EF (kg CH_4 animal^{-1}year^{-1})	EF (kg CH_4 animal^{-1}year^{-1})
Juvenile (< 6 months old)	11.1 (0.4)	4.8 (0.1)	10.2 (0.4)	4.5 (0.2)	5.0
Young male (6–12 months old)	12.6 (0.5)	5.4 (0.2)	14.2 (0.5)	6.2 (0.2)	5.0
Young females (6–12 months old)	12.7 (0.7)	5.4 (0.3)	13.3 (0.8)	5.8 (0.4)	5.0
Intact rams (> 12 months old)	13.8 (0.3)	5.9 (0.1)	13.2 (0.3)	5.8 (0.1)	5.0
Castrated rams (> 12 months old)	12.3 (0.5)	5.2 (0.2)	13.1 (0.4)	5.8 (0.2)	5.0
Ewes (> 12 months old)	12.2 (0.2)	5.2 (0.1)	14.7 (0.6)	6.5 (0.2)	5.0

Values in parenthesis are standard error (SE) of mean

agroecological conditions on feed quality and digestibility in livestock production systems (Mamo et al., 2023).

The estimation of GEI and enteric CH_4 EFs for different categories of sheep provides valuable data for understanding the efficiency of feed utilization and the potential environmental impact of CH_4 emissions. The variations in GEI values across animal classes and between the two Tier 2 estimation methods ('CSIRO' and IPCC) highlight the influence of factors such as body size, growth stage, and metabolic requirements on energy intake. These findings are consistent with Hegarty et al. (2014), who indicated that different animal classes have varying energy requirements, which can influence CH_4 production.

The EF estimated using the 'CSIRO' Tier 2 methodology can be compared to a study conducted in Kenya by Goopy et al. (2021), which focused on different classes of sheep and employed a similar protocol. In their research, they estimated the flock-level EF in various localities in Kenya, ranging from 3.8 to 4.8 (flock-level LW = 23.7 kg), with an overall average of 4.4 kg CH_4 animal^{-1} year^{-1}. However, in the present study, despite the slightly lower flock-level LW of 23.0 kg, the flock-level EF was higher at 5.3 kg CH_4 animal^{-1} year^{-1}. These differences highlight that the LW alone is not the sole determinant of CH_4 production. Other factors such as age in months, which is an integral part of maintenance energy requirement, and distances traveled to estimate energy requirement for activity might contribute to these variations. To draw meaningful conclusions and make accurate comparisons, it is crucial to consider the specific context of the studies, including factors such as animal population, animal characteristics, and feed digestibility and composition (Opio et al., 2013). The same observation applies to EF estimates based on IPCC Tier 2. In the present study, the flock-level EF estimated using IPCC Tier 2 (6.0 kg CH_4 animal^{-1} year^{-1}, average LW=23 kg) was found to be comparable to findings in South Africa, which reported 6.1 kg CH_4 animal^{-1} year^{-1} with 42 kg LW (Du Toit et al., 2013). However, it was substantially higher than the findings in West Africa, which reported 2.3 kg CH_4 animal^{-1} year^{-1} with 17.1 kg LW (Ndao et al., 2019). Besides LW, variations in feed digestibility and average daily weight gain may have a role in the differences among studies. These differences underscore the importance of considering local factors like agroecology. Notably, the EF for sheep in the crop-livestock mixed system in the Ethiopian national livestock GHG inventory in 2018 (Wilkes et al., 2020), (6.9 kg CH_4 animal^{-1} year^{-1}), was higher than the present finding.

The EF estimates for different sheep classes exhibited slight variations between the two Tier 2 models. These subtle differences can be attributed to methodological disparities. Specifically, the 'CSIRO' Tier 2 method accounts for age of the sheep when estimating energy requirements for maintenance, while the IPCC Tier 2 method accounts for energy expenditure for pregnancy. Additionally, the 'CSIRO' Tier 2 model calculates the energy requirement for activity based on the distances traveled by the animals, whereas the IPCC Tier 2 model determines it as a fixed percentage of the energy required for maintenance. As a result of these methodological variations, the IPCC Tier 2 consistently yielded significantly higher EF values for all sheep classes, except for lambs. The discrepancy in the case of lambs can be attributed to the omission of travel-based energy requirements from the EF calculation. The contribution of travel-based energy requirements to the total energy requirement is higher in the IPCC Tier 2 method compared to the 'CSIRO' Tier 2 method, as indicated in Supplemental material Table S2 and Table S3. If travel energy requirements had been considered, the IPCC Tier 2 method would likely have produced higher EF estimates for lambs.

The comparison between the 'CSIRO' Tier 2 and IPCC Tier 2 models in estimating flock-level EF for sheep reveals noteworthy distinctions. One key factor contributing to these differences is the consideration of various sources of energy requirements, which are accounted for by the IPCC Tier 2 model but not by the 'CSIRO' Tier 2 model (IPCC, 2019; Goopy et al., 2021). Specifically, the energy requirements associated with gestation significantly impact the EF estimates for mature ewes in IPCC estimates, as demonstrated in Supplemental material (SM-2) Table S3. Consequently, the IPCC Tier 2 model, which incorporates these energy requirements, yields higher flock-level EF values due to the larger proportion of mature ewes in the study population. The approximately 12.4 % disparity in flock-level CH_4 EFs between the 'CSIRO' and IPCC Tier 2 models may affect the accuracy of GHG inventories. To enhance our understanding and improve the consistency of CH_4 emission estimates, future research should take directly measured intake and emissions and compare them to the Tier 2 estimates to develop better emission equations.

The higher flock-level EFs observed in IPCC Tier 2 methods as compared to the default IPCC Tier 1 value are in line with the findings of Graham et al. (2022), who reviewed GHG emissions from livestock systems in Sub-Saharan Africa. In their study, they reported that sheep had higher Tier 2 EFs compared to IPCC default Tier 1 EFs. The slight difference between Tier 2 flock-level EFs and the Tier 1 default EF can be attributed to the inherent variability among individual animals within the flock, a factor that the Tier 2 methods take into account (Graham et al., 2022), for instance through seasonal live weight measurements. In contrast, the IPCC Tier 1 approach employs a uniform default value of 5.0 kg animal^{-1} year^{-1} for all animals (IPCC, 2019).

Tier 1 method uses default values for the whole African continent. This can be improved by creating regional default values that consider factors such as production systems, conditions, and breeds. The Tier 2 approach takes into consideration the specific characteristics of individual animals, resulting in a more accurate estimation of emissions (Mangino et al., 2003). Although both Tier 2 methods yielded higher flock-level EF compared to Tier 1 default values, the 'CSIRO' Tier 2 method estimated a flock-level EF that is not significantly different from the Tier 1 default EF value. This finding raises the need for further research to verify or delve into the underlying reasons behind this close alignment.

6. Conclusions

This study has yielded valuable insights into the estimation of intake and enteric CH_4 emission factors (EFs) specifically from sheep in smallholder systems. The findings emphasize the significance of

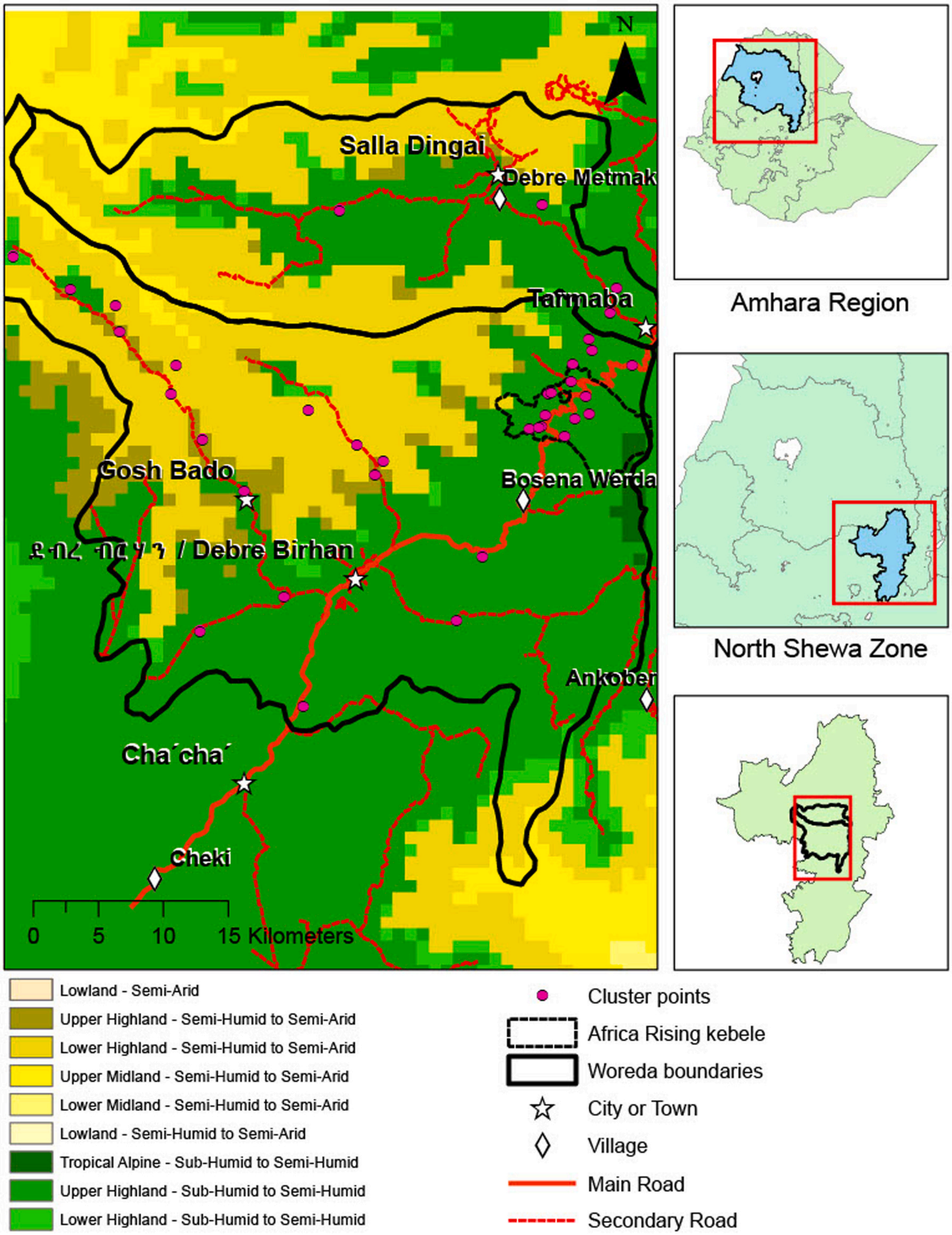

Fig. 1. Study area in North Shewa, Ethiopia. The map shows major agroecological zones (AEZs), the location of sampling cluster points, woreda (district) boundaries, points of interest, and roads. AEZs are based on Sombroek et al. (1982) and Macharia (2004). Map created in Nairobi, Kenya: M. W. Graham,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

considering different sheep classes. Furthermore, the study revealed substantial differences in EFs between Tier 2 estimation methods (’CSIRO’ and IPCC), mainly due to variations in accounting for energy requirements like pregnancy and activity. Future research on directly measured intake and emissions is crucial to refine emission equations and improve Tier 2 estimations. This study reinforces the need for regionalized default values in Tier 1 methods to account for distinct production systems and animal characteristics. By considering these specificities, more precise assessments of enteric CH_4 emissions from sheep in Africa can be achieved.

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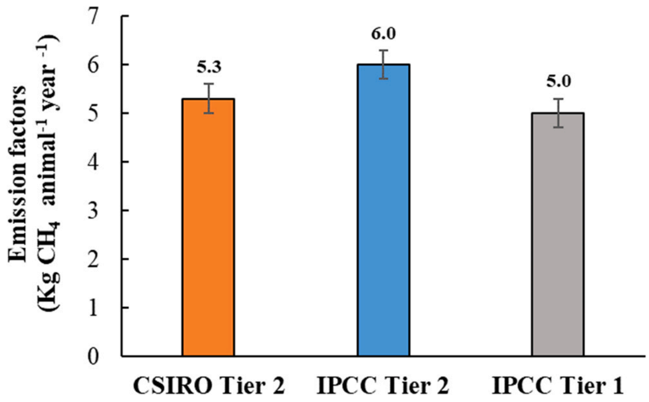

Fig. 2. A comparison between the flock level mean estimated Tier 2 enteric CH_4 emission factors (EFs) for sheep in North Shewa, Ethiopia, and the default IPCC Tier 1 EF showed. Error bars representing estimated mean EFs are expressed as ± 95 % confidence intervals.

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CRediT authorship contribution statement

Phyllis W. Ndung'u: Conceptualization, Formal analysis. **Claudia Arndt:** Project administration, Methodology, Supervision, visualization, writing - review & editing. **Endale B. Gurmu:** Formal analysis, writing-original draft. **Jesse K. Gakige:** Resources, formal analysis. **Tigist Worku:** Resources. **Sonja M. Leitner:** Conceptualization, Methodology, visualization, writing - review & editing. **Michael W. Graham:** Conceptualization, Methodology. **Daniel Getahun:** Investigation. **Andreas Wilkes:** Formal analysis, visualization, writing - review &editing. **Lutz Merbold:** Conceptualization, Methodology, validation, writing - review & editing, Funding acquisition. **Daniel D. Mulat:** Supervision, Formal analysis. **Svenja Marquardt:** Conceptualization, Methodology, Visualization, writing - review & editing. **Dereje Tadesse:** Supervision. **Mekete Bekele:** Supervision.

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

During the preparation of this work the authors used ChatGPT (GPT-4) in order to improve the language and readability of the manuscript. After using this ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical declaration

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.smallrumres.2024.107362.

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