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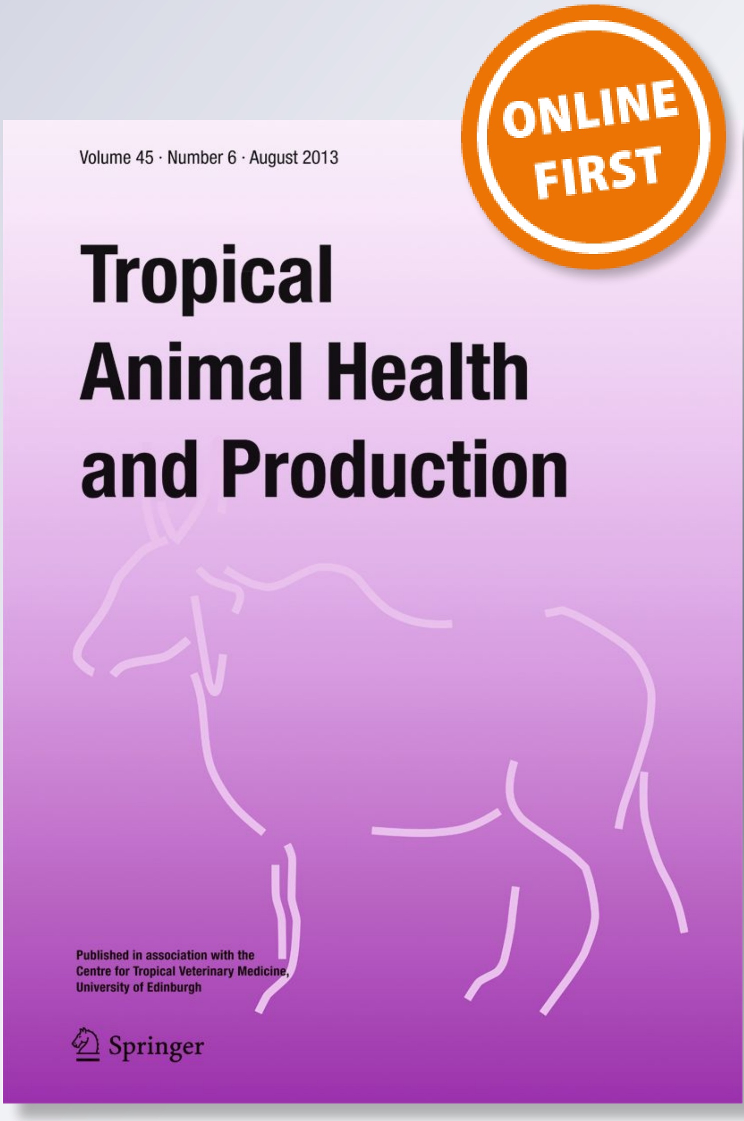

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REGULAR ARTICLES

Contextualized re-calculation of enteric methane emission factors for small ruminants in sub-humid Western Africa is far lower than previous estimates

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Abstract

Given the projected growth of methane emission by ruminants in developing countries, there is a clear need for reliable estimates of their contribution to greenhouse gas emissions. Existing studies have rarely considered sheep and goats. The objective of this study was to predict enteric fermentation methane emission factors (EFs) for *Djallonké* sheep and West African Dwarf goats, following the 2006 IPCC Tier 2 methodology. Estimated enteric methane emission factors, expressed per head of animal per year, were 2.3 kg CH_4 and 2.0 kg CH_4 for sheep and goats species, respectively. Compared with the generic Tier 1 emission factor of 5 kg CH_4 head proposed by the IPCC for small ruminants in the sub-Saharan Africa region, our suggested values are 56% and 60% lower for sheep and goat, respectively. These lower values took account of the particular flock structure of both sheep and goats. These estimates also accounted for differences in live weight according to age and corresponding estimated feed intake. This work is a step forward in the revision of small ruminant emission factors and can further support assessment of mitigation strategies in Senegalese livestock farming systems.

Keywords Enteric methane · Emission factor · Grazing system · Small ruminants · Senegal

Introduction

The history of animal domestication dates back more than 12,000 years (Soren et al. 2015). Small ruminants, i.e., sheep and goats, were the first to be domesticated for human use before other livestock species (Myers 2011).

In the tropics, where most developing countries are located (Preston and Leng 1987), sheep and goats play important roles in nutrition and livelihoods, especially for vulnerable members of society, such as women and children (Kosgey 2004; Missohou et al. 2004; Peacock 2005). In addition, small ruminants (SR) produce manure, which is the main source of organic fertilizer used in traditional production systems of developing countries (Jaitner et al. 2001). Small ruminants are also sold to finance agricultural production inputs during the rainy season (Malick et al. 2015).

In Senegal, SR are an essential component of the livestock economy. Indeed, the large population of SR and their short production cycle compared with that of cattle species allow small ruminants to contribute significantly to meat production. In 2016, sheep and goats in Senegal accounted for 23% of meat production (MEPA 2016).

Despite the numerical importance of small ruminants in Senegal, there have been only limited previous studies of production performance (e.g., liveweight, average daily gain), particularly in extensive systems (e.g., Fall et al. 1982). Some research assessing ruminant productivity constraints has been conducted through the livestock research centers

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(e.g., ISRA/CRZ Dahra and ISRA-CRZ Kolda, located in the semi-arid and subhumid zone, respectively). Another investigation program, called *Programme de productivité des petits ruminants au Sénégal*, was implemented through partnerships between the French Agricultural Research Centre for International Development (CIRAD-EIMVT) and the Senegalese Agricultural Research Institute (ISRA). This latter cooperation provided data on the productivity and the pathology of SR reared in diverse agroecological regions of Senegal (e.g., Faugère and Faugère 1986).

Today, climate change poses significant threats to humans and ecosystems all over the world (Smith et al. 2014), and the West Africa region is particularly vulnerable (Palazzo et al. 2017; Partey et al. 2018). In the agricultural sector of developing countries, livestock is a significant source of GHG emissions (Smith et al. 2014; FAO 2016). In general, it is projected that greenhouse gas (GHG) emissions through livestock activities will continue to increase in developing countries, mostly emitted gas in the form of methane (CH_4) due to enteric fermentation (e.g., Bhatta et al. 2015). In sub-Saharan Africa (SSA), enteric fermentation of ruminants plays a key role in total agricultural emissions (Valentini et al. 2014). Herrero et al. (2008) estimated that in Africa, from 2000 to 2030, methane emissions may increase by 40%.

Enteric methane is a normal product of ruminal fermentation of feed, which is affected by feed composition and quality (Lenka et al. 2015). Methane production tends to increase as the fiber content of feed increases and as the protein content of feed decreases (Johnson and Johnson 1995). Consequently, at a given level of production (milk or meat), ruminants in SSA emit more CH_4 per head than ruminants in developed countries (IPCC 2006; Gerber et al. 2013). However, estimates of CH_4 production in SSA are associated with high uncertainty because emission measurements from grazing ruminants are very limited (Tallec et al. 2012). Therefore, the Tier 1 CH_4 emission factor recommended by the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories suggests to use a default value of 5 kg CH_4 head/year for sheep or goats when detailed information (e.g., reproductive and productive performance) on livestock is not available (IPCC 2006). This default annual methane emission factor (MEF) for small ruminants (i.e., 5 kg CH_4) is often applied in developing countries' GHG inventories (Pelster et al. 2016).

In its last national communication in 2015, Senegal used this default MEF for indigenous sheep and goats (NIR 2015). It is well established that CH_4 production from enteric fermentation varies with diet, grazing period (Archimède et al. 2011; Eugene et al. 2011) and daily dry matter intake (Soren et al. 2015; Hristov et al. 2018). Additionally, the Tier 1 MEF does not take into consideration factors like animal physiology or production level (Cersosimo and Wright 2015). Clearly, compared with Tier 2 and Tier 3 approaches, the default Tier 1 MEF is the less accurate methodology for determining an enteric methane emission factor in a particular context.

The main objective of the present study is to estimate enteric methane emission factors for small ruminants reared in the sub-humid zone of Senegal using the Tier 2 methodology, in order to increase the accuracy of assessments given the context of local livestock production systems.

Materials and methods

Study site and feeding systems

This study was conducted in the sub-humid zone in southern Senegal. In this region, small ruminants are kept in traditional smallholdings that raise diverse types of livestock in integrated crop-livestock systems (Ly et al. 2010). The main pure breeds of small ruminants in this part of the country are the *Djallonke* sheep and the West African Dwarf (WAD) goat (ISRA 2005). These two species are mainly found in West and Central Africa because they are trypanotolerant, i.e., able to survive, reproduce, and remain productive under trypanosomiasis risk without the need for chemicals or drugs to control the vector or parasite (Wilson 1988; Ly et al. 2010). Published estimates of the distribution of small ruminant breeds in Senegal are limited. However, in its latest activity report, the Livestock Ministry estimated their populations at about 6.0 million and 5.2 million for sheep and goats, respectively (MEPA 2016).

Agrosylvopastoral production systems, commonly found in southern Senegal, are characterized by integrated crop-livestock production in which animal production and agricultural crops are concurrently farmed in the same area or sequentially farmed in rotation or succession (Wilson 1988; Fernández-Rivera et al. 2004). Like cattle in the studied region, the most important feed resources for small ruminants are from rangelands, pastures, annual forages, and very scarce purchased concentrate feeds (see Fig. 1). In this region, the use of concentrated feed is very limited, except for during the fattening period before marketing livestock and prior to religious events (Powell et al. 2004; Holechek et al. 2017). However, farmers with sufficient financial resources supplement their animals with concentrate or groundnut leaves (*Arachis hypogaea* L.), which is an important agricultural by-product in Senegal.

During the dry season (November–June), small ruminants graze freely around rangelands and crop fields (Jaitner et al. 2001; Ly et al. 2010). Habitually, the small ruminant herds return to the settlement during the day for watering. At twilight, the herds return to spend the night in a pen. From the onset of the rainy season (May–June) to the harvest period (October–November), the movement of flocks is restricted due to crop production on arable land. Thus, the small

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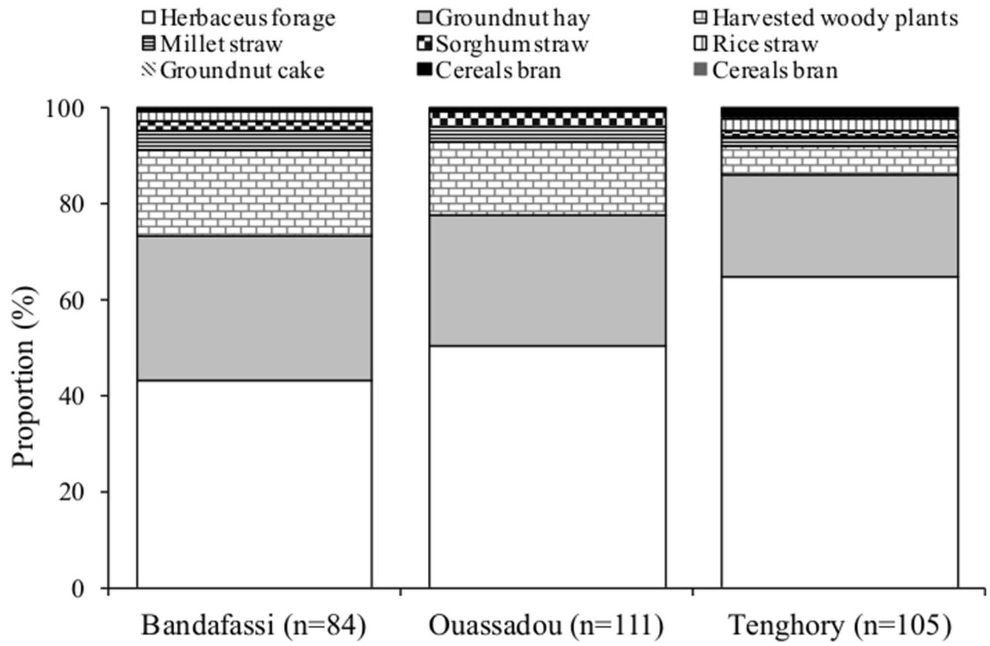

Fig. 1 The main forage types of small ruminants reared in the sub-humid zone of Senegal. These results were obtained through surveys conducted with 300 households located in Bandafassi ($n = 84$), Ouassadou ($n = 111$), and Tenghory ($n = 105$). On a scale from 1 to 10 points, the herd manager of small ruminant allocated importance to each type of forage. Then, for each survey area, the average proportion of each type of forage was calculated

ruminants are tethered in nearby pasture areas (e.g., fallows, bush fields) or grouped into flocks overseen by a shepherd to prevent them from damaging crops.

In Senegal, like in many West African countries, the reproduction system for small ruminants is not seasonal because the ram and the billy goat are always kept with the flock (Kosgey et al. 2006). Hence, lambing and kidding occur throughout the year. In the context of our study site, births are more frequent during the March–May and September–November (Faugère et al. 1990).

Sources of livestock data used

The values of specific input parameters (i.e., herd structure, liveweight (LW, kg), and average daily weight gain (ADG, kg/day)) for each animal class derived from our calculations using the PROGEBE-Senegal database. PROGEBE-Senegal was a project that undertook ruminant monitoring in three different localities in southern Senegal. These areas are *Bandafassi* (12°31′ N, 12°19′ W), *Ouassadou* (13°13′ N, 13°49′ W), and *Tenghori* (12°48′ N, 16°13′ W). In each zone, 20 herds (i.e., 10 flocks of sheep and 10 flocks of goats) were randomly sampled and monitored between 2009 and 2013. Other values were obtained from the database of the Senegalese Agricultural Research Institute (*Institut Sénégalais de Recherches Agricoles*, ISRA) and include research reports, theses, and publications. Additional public data were obtained from the Livestock Ministry of the Senegalese Government (MEPA). However, when information was lacking or no representative data could be identified, references were sourced from published literature or reports of international organizations, such as the Intergovernmental Panel on Climate Change (IPCC). The main criterion for data selection was that the data must come from research conducted in Senegal or in tropical conditions. The justification of this approach is to ensure that the information related to livestock reared on comparable diets and in similar climate conditions and agricultural production systems. All values of input parameters used, including flock structure by ages and sex, and their respective sources are reported in Tables 1 and 2 for sheep and goats, respectively. The Fig. 2 shows details of the proportion of animals in different classes used in this study.

Computation of enteric methane emission factors

To estimate enteric CH_4 emissions from small ruminants, the 2006 IPCC Tier 2 methodology was used. Accordingly, daily gross energy intake (GEI, MJ/day) is estimated for each category of small ruminant (SR), based on their net energy requirements for maintenance, activity, lactation, pregnancy, and weight gain, taking into account the net energy and digestible energy content of feed. Then, the annual enteric methane emission factor (EF) is estimated by multiplying the calculated GEI by the IPCC (2006) default methane conversion rate (Ym, see Volume 4, Chapter 10, Table 10.13), expressing the value on an annual basis taking into account the duration each class of animal is present in the year, and dividing by the energy content of methane (i.e., 55.65 MJ/kg CH_4) (Eq. 1). In order to estimate daily dry matter intake (DMI, kg DM/day), the GEI for each animal category was divided by the energy density of feed (i.e., 18.45 MJ/kg DM) as proposed by the 2006 IPCC guidelines. The energy density of feed enables conversion of GEI into dry matter intake (i.e., kg DMI/day)

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Table 1 Input parameters used to estimate emission factors for enteric fermentation by sheep using the 2006 IPCC Tier 2 methodology and their reference sources

Parameter	Abb.	Unit	Female (age, month)					Male (age, month)					Reference
			[0–3]	[3–6]	[6–12]	[12–24]	> 24	[0–3]	[3–6]	[6–12]	[12–24]	>24	Present study
Flock structure		%	4.1	8.0	11.1	17.5	36.1	3.2	6.2	7.2	5.4	1.2	Present study
Coefficients for calculating NEm	Cfi	MJ day/kg	0.236	0.236	0.236	0.217	0.217	0.236	0.236	0.236	0.217	0.217	IPCC 2006 Table 10.4
Coefficient corresponding to animal's feeding situation	Ca		0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	IPCC 2006 Table 10.5
Average body weight	LW	kg	8.2	12.0	16.9	21.6	26.0	7.8	12.6	17.7	22.8	25.2	Present study
Adult female weight	MW	kg	20	20	20	20	20	20	20	20	20	20	ISRA 2005, 331 pp
Average daily weight	ADG	kg/day	0.220	0.088	0.063	0.040	0.019	0.175	0.095	0.066	0.043	0.025	Present study
Fat content	Fat	%	0	0	0	6	6	0	0	0	0	0	FAO 2018:
Milk yield	Milk	kg/day	0	0	0	0.240	0.240	0	0	0	0	0	Adewumi and Olorunnisomo 2009
Pregnancy	Cp	%	0	0	0	0.077	0.077	0	0	0	0	0	IPCC 2006 Table 10.7
Digestibility	DE	%	70	50	50	50	50	70	50	50	50	50	IPCC 2006 Table 10.2
Methane conversion rate	Ym	%	4.5	6.5	6.5	6.5	6.5	4.5	6.5	6.5	6.5	6.5	IPCC 2006 Table 10.13

Table 2 Input parameters used to estimate emission factors for enteric fermentation by goats using the 2006 IPCC Tier 2 methodology and their reference sources

Parameters	Abb.	Unit	Female (age, month)					Male (age, month)					References
			[0–3]	[3–6]	[6–12]	[12–24]	> 24	[0–3]	[3–6]	[6–12]	[12–24]	> 24	Present study
Flock structure		%	3.6	6.6	11.7	17.2	40.3	2.2	4.3	6.7	5.4	1.9	Present study
Coefficients for calculating NEm	Cfi	MJ day/kg	0.236	0.236	0.236	0.217	0.217	0.236	0.236	0.236	0.217	0.217	IPCC 2006 Table 10.4
Coefficient corresponding to animal's feeding situation	Ca		0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	IPCC 2006 Table 10.5
Average body weight	LW	kg	7.1	9.9	14.4	19.1	24.0	6.6	10.5	13.1	17.9	19.2	Present study
Adult female weight	MW	kg	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7	ISRA 2005, 335 pp
Average daily weight	ADG	kg/day	0.126	0.072	0.054	0.035	0.017	0.128	0.077	0.049	0.034	0.020	Present study
Fat content	Fat	%	0	0	0	4.77	4.77	0	0	0	0	0	Zahradeen et al. 2009
Milk yield	Milk	kg/day	0	0	0	0.22	0.22	0	0	0	0	0	ISRA 2005, 317 pp
Pregnancy	Cp	%	0	0	0	0.077	0.077	0	0	0	0	0	IPCC 2006 Table 10.7
Digestibility	DE	%	70	50	50	50	50	70	50	50	50	50	IPCC 2006 Table 10.2
Methane conversion	Ym	%	4.5	6.5	6.5	6.5	6.5	4.5	6.5	6.5	6.5	6.5	IPCC 2006 Table 10.13

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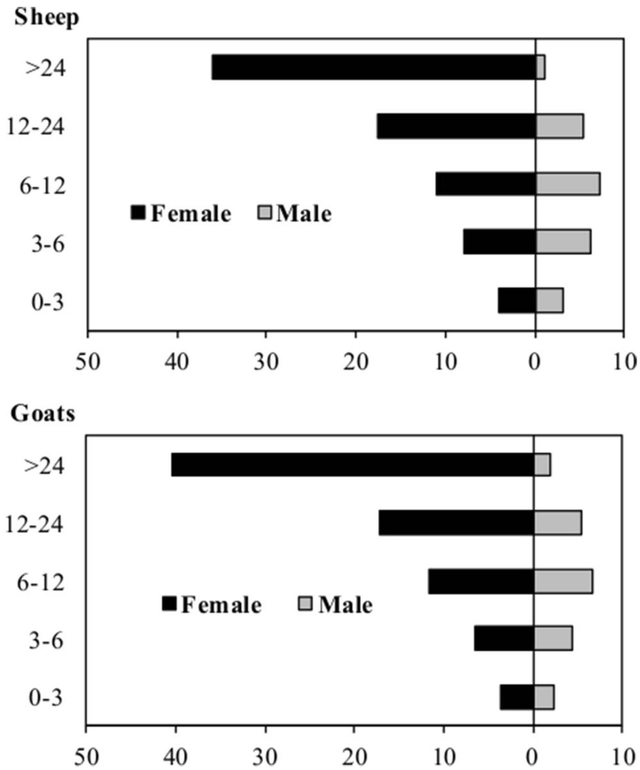

Fig. 2 Age pyramid of small ruminants in the sub-humid zone of Senegal expressed as a proportion of the total population (%). These figures are based on an animal sample of 987 sheep and 1575 goats from localities of Bandafassi, Ouassadou, and Tenghory

for each animal class. The list of formulas used to compute enteric methane emission factors for small ruminants are reported in the Supplementary Materials.

$$\mathrm{EF} = \left[\left(\mathrm{GE}^{*}\left(Y_{\mathrm{m}}/100\right)^{*}365\right)/55.65\right] \quad (1)$$

Where:

EF emission factor, kg CH_4 head/year
GE gross energy intake, MJ head/year
Y_m methane conversion factor, per cent of gross energy in feed converted to methane

The factor 55.65 MJ/(kg CH_4) is the energy content of methane.

Results and discussion

Estimated enteric methane emission factors

The estimated gross energy intake, daily dry matter intake, and annual emission factors for enteric methane from small ruminant sub-categories are reported in Tables 3 and 4, for sheep and goats species, respectively.

Table 3 Estimated dry matter intake based on NE requirements and the emission factor for enteric fermentation by different sub-categories of sheep

Sex	Class (month)	GEI (MJ/hd)	DMI (kg/hd)	MEF (kg CH_4/hd)
Female	[0–3]	1.0	0.06	0.30
	[3–6]	2.0	0.11	0.85
	[6–12]	4.0	0.22	1.71
	[12–24]	6.0	0.33	2.56
	> 24	8.0	0.44	3.41
Male	[0–3]	1.0	0.06	0.30
	[3–6]	2.0	0.11	0.85
	[6–12]	4.0	0.22	1.71
	[12–24]	4.0	0.22	1.71
	> 24	4.0	0.22	1.71

DMI daily dry matter intake, *GEI* daily gross energy intake, *MEF* annual enteric methane emission factor, *hd* head

Overall, our annual weighted enteric fermentation methane emission factors (i.e., at the flock scale) for SR reared in the traditional livestock systems in southern Senegal are 2.3 kg CH_4/head and 1.9 kg CH_4/head for sheep and goats, respectively. Compared with the default annual emission factor (i.e., 5 kg CH_4/head) commonly used for SR in the sub-Saharan Africa region (see IPCC 2006, Table 10.10), our predicted MEFs are 56% and 60% lower for sheep and goats, respectively. These differences between our estimated MEF and the default value recommended by the IPCC are due to the fact that input parameters for Tier 1 are assumed to be representative at the continental scale, while our Tier 2 estimations are specific to the livestock production systems in the Senegalese subhumid zone. Furthermore, the standard MEF recommended in the 2006 IPCC Guidelines for SR in the SSA region is

Table 4 Estimated dry matter intake based on NE requirements and the emission factor for enteric fermentation by different sub-categories of goat

Sex	Class (month)	GEI (MJ/hd)	DMI (kg/hd)	MEF (kg CH_4/hd)
Female	[0–3]	1.0	0.06	0.30
	[3–6]	2.0	0.11	0.85
	[6–12]	2.0	0.11	0.85
	[12–24]	6.0	0.33	2.56
	> 24	6.0	0.33	2.56
Male	[0–3]	1.0	0.06	0.30
	[3–6]	2.0	0.11	0.85
	[6–12]	2.0	0.11	0.85
	[12–24]	4.0	0.22	1.71
	> 24	4.0	0.22	1.71

DMI daily dry matter intake, *GEI* daily gross energy intake, *MEF* annual enteric methane emission factor, *hd* head

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mostly based on investigations reported by Crutzen et al. (1986). In their study, these latter authors noted the scarcity of data related to livestock systems in developing countries. Consequently, Crutzen et al. (1986) adopted a daily gross energy intake (GEI) of 13 MJ for developing countries, based on several assumptions. Then, to estimate the annual MEF for sheep in developing countries, Crutzen et al. (1986) applied the values of 6.0% and 55.65 MJ, corresponding to the methane conversion factor and the energy content of 1 kg methane, respectively. After calculation, Crutzen et al. (1986) obtained and recommended the generic annual MEF of 5 kg CH_4/head for sheep reared in developed countries. The same procedure was used for goats, in which the annual enteric MEF suggested by Crutzen et al. (1986) was based on an average daily GEI of 14 MJ sourced from research conducted in India (see Pandey 1980).

Effect of input parameters used

In our estimates, the herd structure of SR reared in Senegalese traditional livestock systems was taken into account. In the traditional livestock systems of West Africa, numerous classes of SR are grouped in the same feeding system because they are managed as a single group (Kosgey et al. 2006). Thus, to have a population-weighted estimate for the enteric MEF, EFs for distinctive animal classes were calculated, with consideration of their respective proportions in the flock, and the duration of each physiological stage. Therefore, the percentage of certain classes, especially the main emitters of enteric methane (i.e., adult sheep and goats), has a major influence on the annual weighted EF. For example, in our case study, the proportions of adults (i.e., billy goat, ram) are rather high (i.e., 20% and 23% in goats and sheep, respectively), while young animals (< 6 months) are fewer. These particular flock structures can be explained because the category of male adults contributes greatly to annual animal offtake (Lancelot et al. 2002; Ejlertsen et al. 2012), largely during family ceremonies (e.g., baptism, marriages) or religious festivals (e.g., *Tabaski* day for Muslims). Moreover, contagious diseases and other factors (e.g., plague of small ruminants, gastrointestinal parasitism) induce high mortality rates among small ruminants, especially young animals (see Otte and Chilonda 2002; Hammami et al. 2016).

The liveweight (LW, kg) reported for small ruminants in the 2006 IPCC Guidelines (i.e., 45 and 40 kg for sheep and goat, respectively, in SSA region) are higher than those derived from our calculations (Table 1). The LW values used in this study are consistent with those reported in the literature for the same small ruminant species reared in similar regions (see Adebowale 1988; Mourad et al. 2001; Gbangboche et al. 2006; Sowande and Sobola 2008). In order to investigate the importance of using accurate input parameter values in the Tier 2 enteric methane emission factor model, we computed "RandomForest" procedures (Breiman 2001) available in R software (version 3.3.3). The results (Fig. 3) show that LW is the third most important parameter after the maintenance coefficient (Cfi) and the methane conversion rate (Ym). In other words, applying a higher LW in the Tier 2 model for our study zone would result in overestimation of the estimated MEF of small ruminants.

Clearly, this study contributes to the indirect assessment of enteric methane emission factors for small ruminants, using the Tier 2 approach. While our study shows that the Tier 2 method can be applied in developing countries like Senegal, there are known limitations (Wilkes et al. 2017). In particular, because of the lack of data on feed digestibility (DE, %) in the SSA region, we applied a fixed value (i.e., $50 \pm 5\%$) as recommended in the IPCC (2006) Guidelines. However, previous work in the Senegalese subhumid zone suggests that DE can be expected to vary. In the study site, it has been reported that the instantaneous intake rates of Ndama cattle (*Bos taurus*) grazing freely are lowest in the dry season and feed digestibility declines through the early, middle, and late dry season (Ickowicz and Mbaye 2001; Ezanno et al. 2003; Chirat et al. 2014). Considering the relationship between digestibility and the production of enteric methane (Opio et al. 2013; Soren et al. 2015; Sejian et al. 2015), one can assume that methane production fluctuates through the year.

In addition, an expected trend is observed in the region of *Ferlo*, the semi-arid part of Senegal where Doreau et al. (2016), using in vitro approach, reported that CH_4 production potential differs significantly through the seasons. Their results indicate that methane production is greater from February to June (i.e., 29.7–35.2 ml/g DM) and decreases during the rainy season (i.e., 24.6–28.6 ml/g DM) from July to September. In the same vein, adopting the hand plucking approach, Assouma et al. (2018) reviewed the variability of dry matter intake and the digestibility of the forage on rangelands in the *Widou Thiengoly* territory (15°59′N, 15°19′W), northern Senegal. Their research demonstrates that during the wet season, averages intakes are 86.8 ± 12.0 g DM/$LW^{0.75}$ and 90.4 ± 17.1 g DM/$LW^{0.75}$ for sheep and goats, respectively, whereas in the dry season, the average intake values are 66.2 ± 4.7 g DM/$LW^{0.75}$ and 66.8 ± 3.3 g DM/$LW^{0.75}$ for sheep and goats, respectively. Furthermore, using the F-NIRS method, Assouma et al. (2018) showed that feed digestibility decreases from February to June (i.e., dry season) and increases throughout the June–September period (i.e., rainy season). In Eastern Africa, Reid et al. (2005) indicated that forage species in rangelands change in terms of composition and nutritive value, and these factors are associated with variation in feed intake. Furthermore, research conducted in other regions reveals that the CH_4 conversion rate could vary together with changing digestibility of feed and the level of feeding

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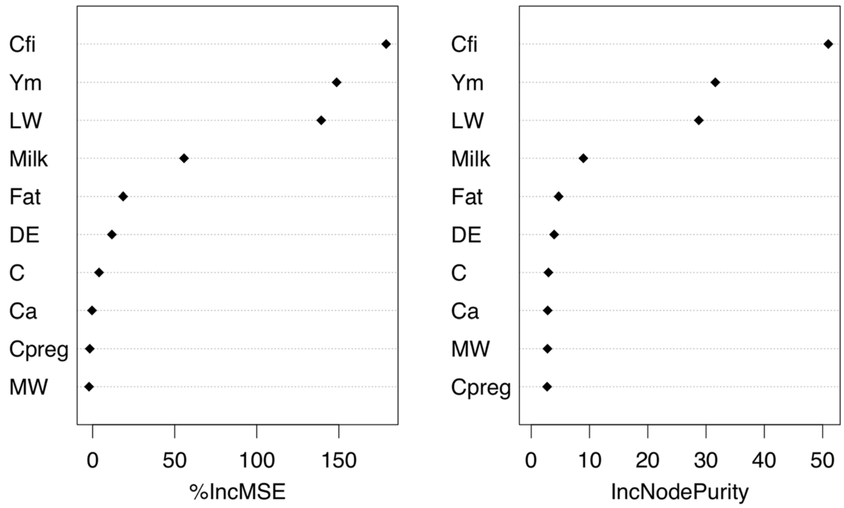

Fig. 3 Importance of input parameters used in the Tier 2 model to predict enteric methane emission factors for small ruminants in the Senegalese sub-humid zone. The figure shows the increase in the mean square error in terms of percentage (%IncMSE) and quality (IncNodePurity) when the parameter is randomly permuted. The parameter is important when the associated %IncMSE or IncNodePurity is higher. In our case, if the important parameters (i.e., Cfi, Ym, and LW) are randomly permuted, they will change greatly the predicted enteric methane emission factor

(Blaxter and Clapperton 1965; Sejian et al. 2015; Hristov et al. 2018). These authors found that gross energy intake increased when the digestibility of feed increased, although there is no simple relationship between these two factors. Significantly, the sub-humid zone is characterized by variation in rainfalls (Cour and Snrech 1998; Fernández-Rivera et al. 2004; Zougmoré et al. 2018), and changes in the length of the plant growing season (Ouédraogo-Koné et al. 2008), both of which are likely to cause variation in the digestibility and availability of feedstuff for grazing animals.

Potential influence of estimated MEF and research perspectives

In Senegal, the total GHGs emitted in 2010 were 13,084 Gg CO_2-e and the agriculture sector was the main source, i.e., 6408 Gg CO_2-e (see NIR 2015). Within the agriculture sector, 77% was from methane gas, with 72% and 5% contributed by enteric methane and rice fields, respectively. According to contribution of livestock to overall agriculture emissions, cattle play the major role (62%), followed by small ruminants (15%) and other species (10%). In light of this profile, enteric methane from ruminants is a key category source in Senegal's national GHG inventory. However, it is important to point out that this inventory is based on the default emission factor of 5 kg CH_4 applied to both sheep and goats. Considering our suggested values, i.e., 2.3 kg CH_4 and 2.0 kg CH_4 for sheep and goats, respectively, which are based on specific input parameter values, the contribution of small ruminants to overall agriculture emission is greatly overestimated (15% vs 7%). Considering the influence of livestock on GHG (and especially methane) emissions, and the inevitable impact of climate change on SSA livestock systems, research should contribute to more accurate enteric MEF estimates. Our work to produce a representative annual MEF for small ruminants in traditional livestock system in Senegal suggests that the use of specific liveweight data is imperative, because the MEF is highly sensitive to this parameter. Furthermore, Senegalese livestock research should investigate the relationships between intake, digestibility, and their impact on MEF development. This approach will require modeling of the MEF though the seasons, because feed availability and digestibility, for example, affect both feed intake and animal performances, and thus the MEF.

The Senegalese Government (SG) is now implementing the *Plan Sénégal Emergent* (PSE, see https://www.sec.gouv.sn/dossiers/plan-sénégal-emergent-pse). The PSE is the official public policy for development and has guided numerous actions through several national projects. Many specific purposes of the PSE address climate change (CC) impacts in Senegal. Furthermore, in accordance with the Paris Agreement, the SG has stated the unconditional objective to reduce national GHG emissions by 5% (i.e., unconditional option) by 2030. However, for this to be achieved, the PSE must fill the gap (40%) in its funds in order to decrease of 21% (conditional option) the total GHG emitted at the national scale.

Examining the SG priority actions, the policies are more focused on adaptation to CC compared with improvement of GHG estimates and mitigation aspects. Through public policies, governments in developing countries need to shoulder research related to mitigation options in the face of CC. For example, to reduce uncertainties, research should improve the calculation of enteric methane which is a key emission source in the overall GHG inventories in many countries in the SSA region. In this regard, various methods have been developed

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by scientists, mainly in developed countries. These methods allow to estimate the enteric MEF for ruminants more accurately. For example, in the USA, respiration chambers are commonly used to measure CH_4 emissions from ruminants (Powers et al. 2014). However, other procedures such as sulfur hexafluoride (SF_6) tracers have been also used (e.g., Kebreab et al. 2006; Deighton et al. 2014; Barbosa et al. 2018).

Despite the expansion of these new measurement tools, the difficulty of quantifying emissions from grazing animals such as those reared in Senegal remains to be overcome (Powers et al. 2014). For example, use of the respiration chamber technique to measure enteric CH_4 losses gives highly accurate results compared with the tracer approach (McGinn et al. 2006). However, the use of chambers requires significant knowledge and is expensive to operate, especially for developing countries (Hammond et al. 2016). Considering the type of livestock systems in Senegal, which is mainly based on natural pastures, we can assume that a direct approach like SF_6 tracers could be adapted to validate the enteric methane emission factor for small ruminants in Senegal.

For mitigation of enteric fermentation emissions, rumen manipulation in order to reduce the methanogenesis (i.e., the production of methane by a group of micro-organisms) is particularly relevant. For example, Garg and Sherasia (2015) reported that for tropical feeding systems, reducing methanogenesis decreases fermentation in the rumen because of the key role of these micro-organisms in H_2 elimination from the rumen. Moreover, the use of concentrate (e.g., feeding of cereal grains) is a potential pathway to decrease enteric methane emissions. However, this mitigation strategy should be employed cautiously because of the ethical concerns over competition between humans and livestock for food security (Powell et al. 2004). Also, due to the diversity of forages in extensive feeding systems in Senegal, the use of phytochemical substances such as tannins could be explored. For example, studies conducted in other regions (e.g., Tavendale et al. 2006; Alves et al. 2017) show very promising ways to mitigate enteric methane emission of ruminants. Other enteric methane mitigation strategies are available but need to be tested in extensive livestock systems, such as those in Senegal, in order to validate their effectiveness. From this perspective, the implementation of this research needs to be supported by governments in developing countries through public policies.

Conclusion

The Tier 2 methodology recommended by the IPCC was used to develop enteric methane emission factors for native *Djallonké* sheep and West African Dwarf goats in Senegal. Our estimates suggest EFs of 2.3 kg CH_4/head/year for sheep and 1.9 kg CH_4/head/year for goats. These emission factors are far lower than the annual default value of 5 kg CH_4/head recommended in the Tier 1 method for Sub-Saharan Africa. However, direct quantification methods are needed to produce more accurate estimates of methane emissions from feed digestion by small ruminants reared in southern Senegalese extensive production systems. Future research should focus on factors (e.g., feed digestibility, dry matter intake, and liveweight) that may contribute strongly to variability in enteric methane production.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflicts of interest.

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