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Emission factors from enteric fermentation of different categories of cattle in the Mexican tropics: a comparison between 2006 and 2019 IPCC

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Abstract

Considerable interest has been shown in evaluating methodologies to calculate current enteric methane emissions and using those that produce the most precise results. The objectives of this study were (1) to calculate the emission factors (EFs) for enteric methane produced by different livestock systems in the Mexican tropics using the Tier-2 methodology of the 2006 IPCC and 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2019 IPCC); (2) to calculate the Tier-2 EFs using both IPCC versions with the methane conversion factor (Y_m) estimated with emission data specific to the Mexican tropics (denoted as Tier-2MX), and (3) to compare the EFs from (2) and (1) based on the Y_m specific to the Mexican tropics and the default Y_m for the 2006 and 2019 IPCC, respectively. To calculate the EFs and Y_m using the Tier-2 methodology, three models of meat production in the tropics were selected: a monoculture system (MC, 6 farms), an intensive silvopastoral system (ISP, 6 farms), and a native silvopastoral system (NSP, 6 farms). Twelve of the selected farms were dual-purpose (meat and milk production), and 6 were used for calf production. The EFs were estimated using two main steps: (1) classification of livestock into subcategories: bulls, lactating cows, dry cows, and replacement heifers; and (2) calculation of the gross energy (MJ day^{-1}) intake as prescribed in Chapter 10, Volume 4 of the IPCC (2006 and 2019). The data showed that high and low productivity could be distinguished using the 2019 IPCC but not the 2006 IPCC. Higher average EFs were generated by Tier-1 than by Tier-2. The Tier-2 EFs were higher than the Tier-2MX EFs. These results confirm that Tier-2 methodologies can enhance existing differences. Additionally, the Tier-2MX EFs for each type of cattle were lower than the Tier-2 and Tier-1 EFs. These results show that it is advisable to use methane yields determined for a particular country or region.

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1 Introduction

Livestock is the second largest source of anthropogenic methane at 54,027.96 gigagrams worldwide (Myhre and Shindell 2011). Anthropogenic methane is a significant greenhouse gas because its global warming potential is 28 times that of carbon dioxide (Greenhouse Gas Protocol 2007). In the Americas region, the highest percentage of biogenic methane gas is emitted by enteric fermentation in cattle at 48.9% (26,422.33 gigagrams) of total emissions. Latin American countries produce 80.7% of the emissions of the Americas and 39.5% of global emissions (FAO 2018).

As Mexico has the third highest number of cattle in Latin America, measured methane emissions in Mexico, as incorporated into the National Inventory of Emissions of Gases and Greenhouse Effect Compounds (SEMARNAT 2018a), have become a benchmark driving management decisions for greenhouse gas mitigation.

Thus, Mexico has shown a notable interest in reducing methane (CH_4) emissions from livestock sources, as reflected by the six National Communications (SEMARNAP 1997; SEMARNAT 2018b, 2012, 2009, 2006, and 2001) submitted at the United Nations Framework Convention on Climate Change (UNFCCC). These reports included the National Inventory of Emissions of Gases and Greenhouse Effect Compounds (INEGYCEI) by sector, which highlights bovine livestock as one of the main sources of emissions (SEMARNAT 2018a). Of the total greenhouse gas (GHG) emissions for Mexico (682,959.1 Gg of CO2-e ± 7.68% in 2015), livestock produces 10% (70,567.60 Gg of CO2e ± 4.78%), of which 76% are produced by enteric fermentation of cattle (53,442.72 Gg of CO2e ± 6.11%), and 24% are associated with manure management (17,124.88 Gg of CO2e ± 4.96%) (SEMARNAT 2018a).

National inventories of CH_4 emissions from enteric fermentation of cattle are currently estimated using the Tier-1 methodology of the Intergovernmental Panel on Climate Change (IPCC), which calculates methane emissions per animal category (i.e., cattle, buffalo, sheep, goat, horse, and pig) by multiplying the animal population by the average emission factor for the respective category (IPCC 2006). The Tier-1 emission factor (EF) determined by the Guidelines for National Greenhouse Gas Inventories (IPCC 2006) is 56 kg CH_4 $year^{-1}$ per head of cattle based on grazing in Latin America, assuming similar weights, ages, sexes, and feeding systems within each animal subcategory; however, the estimated reliable value of the EF is considered to be associated with a large uncertainty (Mach et al. 2017). Mexico used this EF to determine that cattle account for 87.46% of the emissions of the livestock sector in Mexico (SEMARNAT 2018a).

The Tier-2 methodology (IPCC, 2019) is more complex than the Tier1 methodology in requiring detailed country-specific data for the gross energy intake and methane conversion factors for specific livestock categories. This method should be used if enteric fermentation is a key source of a country's total emissions for the respective animal category. Thus, the IPCC (IPCC 2019) urges countries with a high livestock inventory, as is the case in Mexico with 33,918,906 heads (9th place worldwide; FAOSTAT (2017), to estimate emission factors to increase the accuracy of emission inventories. Therefore, the generation of local methane emission factors for ruminants has become a challenge for Mexico (FAO and New Zealand Agricultural Greenhouse Gas Research Centre 2017).

CH_4 emission data from enteric fermentation were recently determined by Ku-Vera et al. (2018), who suggested that the estimated methane emissions inventory can be improved. Ku-Vera et al. (2018) determined the production of ruminal CH_4 by crossbred cattle fed a typical tropical diet in Mexico (tropical grasses as basal ration and at least 20% of the dry matter (DM) ration of a commercial concentrate) using open-circuit respiration chambers. The respiration chamber technique is considered the most accurate for the measurement of enteric CH_4 in ruminants (Hammond et al. 2016). The authors correlated CH_4 production with the DM intake (DMI) and GEI. The CH_4 performance (18.07 g CH_4/kg DMI) predicted by regressing the DM intake (kg/day) against methane production (g/day) was concluded to be reliable for estimating enteric CH_4 inventories of grazing cattle in the tropical region of Mexico. The corresponding percentage of the gross energy intake lost as methane (Y_m) is 5.92%, which is less than the default value of 6.3% proposed by the IPCC (2019).

The recently published 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (hereafter, referred to as 2019 IPCC) provides updated default values of emission factors and other parameters based on the most recent available scientific information only when significantly different from those provided in the 2006 IPCC Guidelines (Calvo et al. 2019). The newly updated CH_4 EFs of the 2019 IPCC are based on feed characteristics (energy digestibility; neutral detergent fiber, i.e., the proportion of feed composed of insoluble fibers, hemicellulose, cellulose, lignin, and some protein fractions; and forage percentage) and animal productivity. These updates may enable GHG inventories for Mexico to be calculated more precisely than by using the 2006 IPCC Guidelines.

Different research groups worldwide are trying to accurately determine enteric methane emissions from cattle to reduce the uncertainty of methane inventories for several countries (Charmley et al., 2016; Escobar-Bahamondes et al., 2017; Hristov et al., 2018; Eugène et al. 2019). Livestock feed management strategies to mitigate GHG emissions have been investigated in Mexico, and specialists understand that methodologies to accurately calculate enteric methane emissions are required. Thus, these specialists have evaluated different methodologies to select those that can most accurately predict enteric methane emissions and support decision-making regarding livestock management (Benaouda et al. 2020).

We consider the development of enteric methane emission factors specific to livestock regions to be a worthwhile effort at the national level for preventing overestimation or underestimation of enteric methane emissions in livestock inventories. Our aim is to characterize the main production systems throughout the country using region-specific emission factors to reduce uncertainties in mitigation planning studies.

In light of the issues presented above, the objective of this study is to calculate Tier-2 emission factors for cattle using methane emission data specific to the Mexican tropics and comparatively assess the Tier-1 and Tier-2 predictions of the 2006 and 2019 IPCC.

2 Materials and methods

The data used in this study was obtained for the states of Veracruz and Yucatan in the Mexican tropics, the region of Mexico with the highest cattle production (44% of the meat produced in the country) (SIAP, 2020). Three municipalities in Yucatan state, Merida (20°58′01″ N, 89°37′28″ W), Tzucacab (20°04′19″ N, 89°03′01″ W), and Tizimin (21°08′36″N, 88°09′07″ W), and three municipalities in Veracruz state, Martínez de la Torre (20°04′24.196″N, 097°03′13.824″W), Ursulo Galvan (19° 24′ 34.38″N, 96° 22′ 33.132″W) and Los Tuxtlas (95° 11′ 36.489″W, N 18° 39′ 42.653″W), were selected.

To calculate the EFs and Y_m using the Tier-2 approach, different models of meat production in the Mexican tropics were selected: (a) a monoculture system (MC, 6 farms), (b) an intensive silvopastoral system (ISP, 6 farms), and (c) a native silvopastoral system (NSP, 6 farms). The EFs were calculated based on information obtained through a series of semistructured interviews with owners of a total of 18 cattle farms, of which 12 were dual-purpose (meat and milk production) (González-Quintero et al. 2020) and six were used for calf production. The semistructured interviews were conducted to identify the type of cattle management used (the feeding method and production parameters, e.g., body weight, milk production, and weaning age).

(a) MC farms are characterized by grazing cattle on *Brachiaria decumbens*, *Brachiaria brizantha*, *Cynodon nlemfuensis*, *Cynodon dactylon*, *Panicum maximum*, and *Pennisetum purpureum* pastures as the main food source, supplemented by a commercial concentrate based on corn and soy.
(b) On ISP farms, the animal diet is based on both grasses (*Brachiaria decumbens*, *Brachiaria brizantha*, *Cynodon nlemfuensis*, and *Cynodon dactylon*) and legumes such as *Leucaena leucocephala* (*L. leucocephala*) and *Arachis pintoi*. The animal diet is also supplemented by commercial concentrate.
(c) In NSP farms, the animal diet is based on native vegetation and, to a lesser extent, the grasses *Brachiaria decumbens*, *Brachiaria brizantha*, *Cynodon nlemfuensis*, *Cynodon dactylon*, *Digitaria decumbens*, *Panicum maximum*, and *Paspalum notatum*.

2.1 Methane emission factors

To determine the quantity of methane produced by livestock, known as the emission factor (Ominski et al., 2011), livestock were classified into subcategories, and the gross energy intake (GEI) was then calculated as prescribed in Chapter 10, Volume 4 of the IPCC (IPCC 2006, 2019).

2.1.1 Classification of cattle into subcategories

Cattle were categorized into (heads/% of the total population) (a) bulls (33/2.2%), which refer exclusively to males over 1 year old destined for reproduction; (b) lactating cows (737/47.9%), corresponding to females who were intended for breeding or had already had a calf or were breastfeeding at the time of the study; (c) dry cows (469/30.45%), which include females destined for breeding that had had at least one calf or one calving and were not breastfeeding at the time of the study; and, finally, (d) replacement heifers (300/19.48%), defined as females older than 1 year, who had been weaned, were destined for breeding and had not had a calf or calving at the time of the study.

2.1.2 Calculation of energy intake of animals

The calculation of EFs using the IPCC Tier-2 methodology requires data on food intake (kg DM/head/day) for a representative animal of each subcategory. In general, food intake is measured in terms of the gross energy (GE) (e.g., MJ day^{-1}) or dry matter (kg DMI day^{-1}) (corresponding to a simplified methodology denoted as Tier-2D) (IPCC 2019); the EFs were calculated in this study in terms of the GE.

The net energy required for maintenance (NE_m) was estimated from the input data and included the net energy for growth (NE_g), the activity carried out (NE_a), pregnancy (NE_p), and milk production (NE_l). The equations used to calculate the net energies are presented in Table 1. The input data were the average body weight of the animals, the daily weight gain, the mature weight, feeding situation, daily average milk production, the fat content of milk (percent), percentage of females that calved at 1 year, and the region-specific enteric methane emissions determined by the 2006 and 2019 IPCC.

The energy calculation was performed for a 1-year period. To calculate NE_l in dual-purpose units, a milking period between six and 10 months was considered, and in calf-producing farms, the corresponding period from birth to weaning for a calf was taken as ranging between 4 and 8 months; therefore, these energy data were not used for the group of lactating females for the rest of the year. In addition, the GE content of the food ingested was determined considering 17 MJ/kg DM for tropical forage (Castelán-Ortega et al. 2014).

Enteric methane EFs were estimated using Eq. 10.21 of the 2019 IPCC:

$$\mathrm{EF} = \left[\mathrm{GE} \times \left(\mathrm{Y_m}/100\right) * 365)/55.65\right]$$

where

EF = emission factor (kg CH_4 head^{-1} year^{-1});
GE = GE intake, MJ head^{-1} day.$^{-1}$; and
Y_m = methane conversion factor, i.e., the percentage of the GE intake converted to methane;
The factor 55.65 (MJ kg^{-1} CH_4) corresponds to the energy content of methane.

In this study, enteric methane EFs were derived using the default methane conversion factor (Y_m) for the IPCC Tier-2 methodology (denoted as Tier-2D EFs). EFs were also calculated using the same methodology and a Y_m was estimated considering the characteristics of the herd and typical diet of the Mexican tropics (denoted as Tier-2MX EFs). The Y_m used to calculate the Tier-2MX EFs was estimated using the following equation:

$$Y_m\ (\%\ \mathrm{GEI}) = \left(\mathrm{CH_4\ MJ\ day^{-1}}\left(\mathrm{MJ/DMI\ day^{-1}}\right) * 100\right)/\mathrm{GEI\ in\ MJ\ day^{-1}}$$

where

GEI is the GE intake in MJ day.$^{-1}$ obtained from Eq. 10.16 (Eq. 8, Table 1), and
CH_4 MJ day^{-1} was taken as 18.07 g kg DMI^{-1}, as determined by Ku-Vera et al. (2018).
Y_m was calculated to be 6.5% and 7.0% using Table 10.12 of the 2006 and 2019 IPCC, respectively, and 5.92% for Tier-2MX (calculated following Ku-Vera et al. (2018))

The estimates were compared with the default Tier-1 EFs. An EF of 56 kg CH_4 head^{-1} year^{-1} was proposed in the 2006 IPCC (Table 10.11) for all animal subcategories, whereas EFs of 56 and 58 kg CH_4 head^{-1} year^{-1} were proposed for cattle for high- and low-productivity systems in the Latin American region, respectively, in Table 10.11 of the 2019 IPCC. According to the FAO (2014) (referenced in the 2019 IPCC), "high-productivity systems are based on animal feeding systems using high-quality grass and

Table 1 Equations used to calculate Tier-2 emission factors, based on the IPCC (IPCC. 2006, 2019)

Eq.	Metabolic function and other estimates	Equation	Data
1	Net energy for maintenance (NE_m) MJ day^{-1}	$\mathbf{NE_m = Cf_i \times (weight)^{0.75}}$ NE_m = net energy for maintenance Cf_i = coefficient that varies for each animal category. Lactating cows = 0.386; non-lactating cows = 0.322; bulls = 0.370. Table 10.4 (IPCC, 2019) Weight = animal body weight (see Table 2)	Equation 10.3 (IPCC, 2006 and IPCC, 2019)
2	Net energy for activity (NE_a) MJ day^{-1}	$\mathbf{NE_a = C_a \times NE_m}$ NE_a = net energy for animal activity MJ day^{-1} C_a = coefficient corresponding to animals feeding situation. 0.17 in MC and SP; 0.36 in NSP Table 10.5 (IPCC, 2019)	Equation 10.4 (IPCC, 2006 and IPCC, 2019)
3	Net energy for growth (NEg) MJ day^{-1}	$\mathbf{NE_g = 22.02 \times (BW/C \times MW)^{0.75} \times WG^{1.097}}$ BW = average live body weight in the population, kg (see Table 2) C = a coefficient with a value of 0.8 for females, 1.0 for castrates, and 1.2 for bulls (IPCC, 2019) MW = the mature live body weight of an adult animal in moderate body condition, kg (see Table 2) WG = the average daily weight gain of the animals in the population, kg day^{-1} (see Table 2)	Equation 10.6 (IPCC, 2006 and IPCC, 2019)
4	Net energy for lactation (NE_l) MJ day^{-1}. Not applicable in heifers	$\mathbf{NE_l = milk \times (1.47 + 0.40 \times fat)}$ NE_l = net energy for lactation MJ day^{-1} milk = kg of milk day^{-1} (see Table 2) fat = fat content of milk % (see Table 2)	Equation 10.8 (IPCC, 2006 and IPCC, 2019)
5	Net energy for pregnancy (NE_p) MJ day^{-1}	$\mathbf{NE_p = CPregnancy \times NE_m}$ NE_p = net energy required for pregnancy, MJ day^{-1} $C_{pregnancy}$ = in heifers 0.10. It was not applied in lactating cows Table 10.7 (IPCC, 2019)	Equation 10.13 (IPCC, 2006 and IPCC, 2019)

Table 1 (continued)

Eq.	Metabolic function and other estimates	Equation	Data
6	Ratio of net energy available in diet for maintenance to digestible energy intake (REM) MJ day^{-1}	$\mathbf{REM = [1.123 - (4.092 \times 10^{-3} \times DE\%) + [1.126 \times 10^{-5} \times (DE\%)^2] - (25.4/DE\%)]}$	Equation 10.14 (IPCC, 2006 and IPCC, 2019)
		REM = ratio of net energy available in diet for maintenance to digestible energy intake	
		DE% = digestible energy expressed as a % of GE	
		DE% = 65 in MC, 60 in ISP; 55 in NSP (Table 10.2, IPCC, 2006)	
		DE% = 67.5 in MC, 60 in SP; 55 in NSP (Table 10.2, IPCC, 2019)	
7	Ratio of net energy available for growth in a diet to digestible energy intake (REG) MJ day^{-1}	$\mathbf{REG = [1.164 - (5.160 \times 10^{-3} \times DE\%) + [1.308 \times 10^{-5} \times (DE\%)^2] - (37.4/DE\%]}$	Equation 10.15 (IPCC, 2006 and IPCC, 2019)
		REG = ratio of net energy available for growth in a diet to digestible energy intake	
		DE% = digestible energy expressed as a percentage of gross energy	
8	Gross energy (GE) MJ day^{1}	$\mathbf{GE = [(NEm + NEa + NEl + NEmob + NEp/REM) + (NEg/REG)/(DE\%/100)]}$	Equation 10.16 (IPCC, 2006 and IPCC, 2019)
		GE = gross energy intake, MJ head^{-1} day^{-1}	

concentrates in confinement production systems or grazing with supplements or on improved pastures, producing high rates of daily weight gain. Animals can be purebred or crossbred and are genetically improved through selective breeding for improved commercial meat production." Likewise, "low-productivity systems are based on animal feeding systems where locally produced roughage (e.g., crop residues) or low-quality rangelands represent the major source of feed utilized, producing low rates of daily weight gain. Animals can be represented by local breeds or may be crossbred and can also be used for multiple purposes, such as draft, meat, and milk for personal consumption and markets."

In this study, the monoculture and intensive silvopastoral systems were assumed to be high-productivity systems because the cattle in these systems graze on improved pastures and are fed legumes supplemented with concentrates and were thus assigned an EF of 56 kg CH_4 head^{-1} year^{-1}; the native silvopastoral system was considered a low-productivity system and therefore assigned an EF of 58 kg CH_4 head^{-1} year^{-1}.

The equations used to calculate the gross energy intake are shown in Table 1. The activity data are listed by the production system in Table 2.

3 Results and discussion

The enteric CH_4 Tier-2 EFs (i.e., using the Tier-2D and Tier-2MX methodologies from both the 2006 and 2019 IPCC) for all the production systems ranged from 26.6 to 67.6 kg CH_4 head^{-1} year^{-1} with an average of 46.9 kg CH_4 head^{-1} year^{-1} (Table 3), whereas the average default Tier-1 EF was 56.3 kg CH_4 head^{-1} year^{-1}. That is, the average Tier-2 EF was 16.8% lower than the average Tier-1 EF.

The updated default EFs for enteric fermentation in cattle based on the Tier-1 approach proposed in the 2019 IPCC were different for low- and high-productivity grazing systems (58 and 56 kg CH_4 head^{-1} year^{-1}, respectively), making it possible to distinguish the NSP system from the MC and ISP systems (Fig. 1). This distinction could not be made using the 2006 IPCC guideline of 56 kg CH_4 head^{-1} year^{-1} for all grazing-based cattle production systems in Latin America.

A comparison of the average default Tier-1 EFs (2006 and 2019 IPCC) and the average Tier-2D and Tier-2MX emission factors (2006 and 2019 IPCC) showed that the average default EF was slightly higher (1.2%) for the 2019 IPCC (56.7 kg CH_4 head^{-1} year^{-1}) than for the 2006 IPCC Tier-1 (56 kg CH_4 head^{-1} year^{-1}). Likewise, the average EF was 6.0% higher for the 2019 IPCC Tier-2D (51.8 kg CH_4 head^{-1} year^{-1}) than the 2006 IPCC Tier-2D (48.6 kg CH_4 head^{-1} year^{-1}). These results show a tendency toward higher methane EFs in the 2019 IPCC, as reported by González-Quintero et al. (2021). This difference can mainly be attributed to the higher percentage of digestibility of food assumed for the MC system in the 2019 IPCC than in the 2006 IPCC (Table 10.12 of the 2019 IPCC establishes the percentage digestibility of the feed per livestock category and type of production). Furthermore, a higher Y_m is proposed for nondairy cattle with forage-based diets in the 2019 IPCC (7.0%) than in the 2006 IPCC (6.5%).

The higher average for Tier-1 EFs than Tier-2D and Tier-2MX is attributed to the uncertainty associated with region-specific diet management characteristics based on expert opinion used in Tier-1 (Mach et al., 2017; Parra and Mora-Delgado 2017).

Likewise, the lower Tier-2MX EFs compared to the Tier-2D EFs and Tier-1 show that both EFs may overestimate enteric CH4 emissions from cattle in the Mexican tropics and

Table 2 Detailed activity data by system

	Average body weight * (BW)	Weight gain* (WG)	Feeding situation$^{(1)}$	Daily average milk production*	Fat content of milk (percent)$^{(2)}$	Mature weight (MW)	Percentage of females that give birth in a year	Emission of enteric methane specific to the region	
Monoculture				7.67	3.48		0.675	2006[a]	2019[b]
Bulls	601	0.30	Pasture			420		56	56
Lactating cows	475	0.30	Pasture			580[a]		56	56
Non-lactating cows	475	0.30	Pasture			420		56	56
Heifers	289	0.30	Pasture			285*		56	56
Intensive silvopastoral				6.92	3.48		0.650		
Bulls	562	0.3	Pasture			420		56	56
Lactating cows	488	0.3	Pasture			580[a]		56	56
Non-lactating cows	496	0.3	Pasture			420		56	56
Heifers	300	0.3	Pasture			285*		56	56
Native silvopastoral				7.17	3.48		0.650		
Bulls	613	0.25	Grazing large areas			420		56	58
Lactating cows	467	0.25	Grazing large areas			580[a]		56	58
Non-lactating cows	467	0.25	Grazing large areas			420		56	58
Heifers	285	0.25	Grazing large areas			285*		56	58

*Data provided by farmers

(1) Page 110, Chapter 4, Vol 10, IPCC (2019), Table 10A.3

(2) Juárez et al. (2016)

[a] IPCC, 2006

[b] IPCC, 2019

Table 3 Emission factors Tier-1, Tier-2D, and Tier-2MX of four animal subcategories by animal production system in the Mexican tropics. *MC* monoculture, *ISP* intensive silvopastoral, *NSP* native silvopastoral

		Tier-1 2006	Tier-1 2019	Tier-2D 2006	Tier-2D 2019	Tier-2MX 2006	Tier-2MX 2019
System	Subcategory	kg CH_4 $head^{-1}$ $year^{-1}$					
MC	Bulls	56	56	44.3	45.2	40.3	38.2
MC	Lactating cows	56	56	48.7	49.9	44.3	42.2
MC	Dry cows	56	56	44.0	44.9	40.0	38.0
MC	Heifers	56	56	30.9	31.4	28.1	**26.6**
ISP	Bulls	56	56	47.0	50.6	42.8	42.8
ISP	Lactating cows	56	56	53.2	57.3	48.4	48.4
ISP	Dry cows	56	56	51.3	55.2	46.7	46.7
ISP	Heifers	56	56	36.1	38.8	32.8	32.8
NSP	Bulls	56	58	62.6	67.4	57.0	57.0
NSP	Lactating cows	56	58	62.7	**67.6**	57.1	57.1
NSP	Dry cows	56	58	57.7	63.9	52.5	54.0
NSP	Heifers	56	58	42.8	46.0	38.9	38.9

*Values in bold represent the lowest and highest EFs

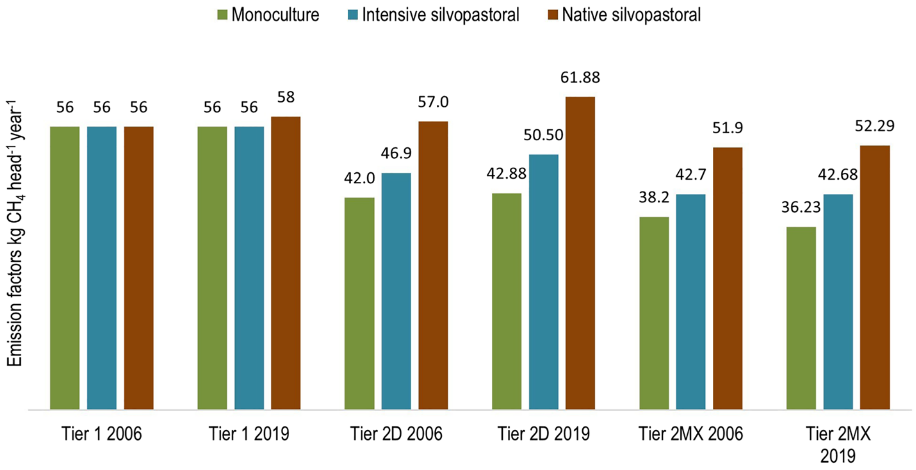

Fig. 1 Comparison of default Tier-1 and Tier-2D and Tier-2MX emission factors (kg CH_4 $head^{-1}$ $year.^{-1}$) estimated using the 2006 and 2019 IPCC for three cattle production systems in the Mexican tropics

therefore the data reported in the National Inventory of Emissions of Gases and Greenhouse Effect Compounds for Mexico since they are based on estimates with Tier-1 EFs (SEMARNAT 2018a).

The equations to estimate the NE_m used to calculate the Tier-2 EFs may be biased (resulting in an overestimate) given that different net energies are needed for the maintenance of *Bos indicus* and *Bos taurus* cattle and their crossed offspring (Vercoe 1970). Animals of zebu breeds and their crossbreeds are predominant in the Mexican tropics. Therefore, to reduce the uncertainty in the Tier-2 EFs, the NE_m should be calculated using the specific energy requirements of the prevalent cattle crosses in the region.

The lower Tier-2D and Tier-2MX emission factors compared to the Tier-1 EFs can be explained by the corresponding methodologies allowing for the inclusion of information other than population data, including feeding strategies and the duration of time in a given production environment (Ominski et al. 2011). The results of our study are consistent with those of Ricci et al. (2013), who found that using an improved model to predict methane emissions impacted the final carbon budget of the entire farm under consideration, whereby the predicted enteric CH_4 decreased by 10 to 17%, depending on the type of system. Similarly, the average EF was higher for Tier-2D than Tier-2MX because the Tier-2D EFs were calculated based on the methane yield value proposed by the IPCC, whereas the Tier-2MX EFs were estimated based on methane emissions specific to the Mexican tropics (as explained in Sect. 2.1.2). Based on these results, it could be argued that a lower uncertainty is associated with the Tier-2MX EFs than the Tier-1 and Tier-2D EFs and that specific livestock production data can be used to develop more precise region-specific EFs.

Considering the results presented above, the application of the three methodologies produced a methane emission potential from enteric fermentation for the NSP system between 26.4 and 30.7% higher than the MC and between 17.8 and 18.4% higher than the ISP. Within the Tier-2 approach (Tier-2D and Tier-2MX), this difference could be attributed to the incorporation of the quantity of gross energy per day required by animals in the NSP system via an activity coefficient (Ca). The Ca of the native silvopastoral system is 111% higher than that of the intensive silvopastoral and monoculture systems (i.e., 0.36 for animals on large grazing areas vs. 0.17 for animals on pasture; Eq. 10.4, Table 10.5, IPCC (2019)). An additional difference among the systems is that the percentage of digestibility of cattle feed assumed by the 2006 and 2019 IPCC for the NSP (based on native plants and low-quality forages) is 15.4% and 18.5% lower than for the MC system, respectively, and 8.3% and 9.8% lower than the ISP system, respectively. The difference in the digestibility percentage is assumed because both the MC and ISP animal diets are based on improved pastures and a mixed-diet feed (pasture and grains or commercial feed), which have higher digestibility than the NSP animal diet.

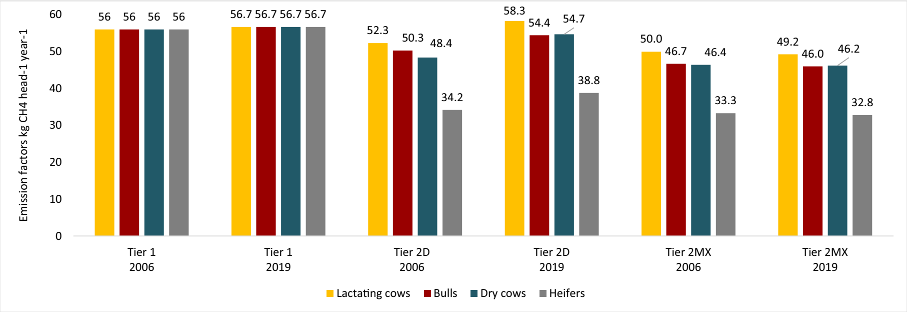

Fig. 2 Comparison of methane emission factors for enteric fermentation using three methodologies based on the 2006 and 2019 IPCC

Figure 2 is a comparison of the emission factors by animal subcategory. The data corroborate the null discriminatory power of Tier-1 and confirm that Tier-2 methodologies can enhance existing differences. Additionally, these results show that the estimated Tier-2MX EFs for each type of cattle are lower than the Tier-2D and Tier-1 EFs. These results confirm the assertion of Nemecek et al. (2016) and Charmley et al. (2015) that it is advisable to use methane yields estimated for a particular country or region. The aforementioned authors found that recalculating inventories using nationally estimated values resulted in a significant reduction from previously estimated volumes of methane emissions. The feed energy digestibility and cattle energy intake level are two significant factors that affect enteric CH_4 emissions (Benaouda et al. 2020; Liu et al. 2017). Therefore, both the quality and composition of an animal diet (as determined by the feed forage-to-concentrate ratio and the geographic region for grazing cattle, for example) could affect feed digestibility (Hook et al. 2010) and therefore, enteric methane emissions.

The estimated EFs show that among the animal subcategories, the highest potential for methane emissions by enteric fermentation is associated with lactating cows, followed by bulls, dry cows, and heifers. These results are consistent with the energy requirements of the different animal subcategories (because lactating cows require the most energy) and the results of Benaouda et al. (2020). The aforementioned results show that Tier-2 EFs can be used to discriminate among animal subcategories and production systems, which can support decision-making for the management of livestock systems.

Our results showed that the Tier-2MX EFs calculated using a Y_m based on a methane yield for cattle specific to the Mexican tropics (Ku-Vera et al. 2018) were lower than the Tier-2 and Tier-1 EFs. These results demonstrate the importance of using region-specific data to estimate inventories of greenhouse gas emissions from cattle.

It is important to mention that the contribution of including *L. leucocephala* in the animal diet to the methane emissions was not estimated for the intensive silvopastoral system. This omission was made because the percentage of this legume included in the diet could not be accurately calculated. This issue is significant because the inclusion of *L. leucocephala* in animal diets has been shown to mitigate methane emissions and could support the mitigation potential of intensive silvopastoral systems (Harrison et al. 2015; Piñeiro-Vázquez et al. 2018). Estimating the contribution of legumes to the reduction of CH_4 emissions could enable the identification of effective mitigation measures adopted specifically by the livestock sector. Such estimates would increase the robustness and reduce the uncertainty of estimated EFs.

Uncertainties are associated with each item of information used to characterize the cattle population within the Tier-2 methodology of the 2006 IPCC, where the magnitude of the uncertainty depends on the method of data collection. There may be uncertainties in the Tier-2 EFs estimated in this study associated with population data; animal body weight; management practices; ingredients, digestibility, and chemical composition of diet; feeding strategy; and performance data (e.g., milk production and body weight gain). The dry matter intake is a critical input for the accurate prediction of livestock enteric CH_4 emissions (Hristov et al. 2018; Lassey 2007; Ominski et al. 2011). However, the prediction of dry matter intake in the Mexican tropics continues to be challenging due to prevailing grazing conditions, such as variability in both the nutritional characteristics of the pasture with the climatic seasons and the grazing time.

We recognized that using the predetermined digestible energy values of feed proposed in the 2006 and 2019 IPCC (that are not specific to the local cattle diet) influences the robustness of the EFs estimated by the Tier-2D and Tier-2MX methodologies. However, the Tier-2MX EFs reflect considerable progress in estimating emissions from the livestock sector in Mexico. In some studies, lower uncertainties have been reported for EFs estimated using the IPCC Tier-2 methodology than for Tier-1 EFs, although the magnitudes of the uncertainties were not specified (Ominski et al., 2011; Parra and Mora-Delgado 2017).

We recommend that the measurement of methane emissions at the regional level be continued to increase the precision of GHG emissions inventories for Mexico. Given the wide distribution of cattle throughout Mexico, region-specific information would support climate decision-making. This strategy would be in line with the recommendations of Group II (Impact, Vulnerability, and Adaptation) of the Mexican Climate Change Report (Gay and Clemente 2015) that the emissions inventory must be sensitive to local and regional information and context. Emission inventories can thus serve as a basis for the application of appropriate measures to reduce enteric methane emissions following the Paris Agreement within the UNFCCC and the Sustainable Development Goals.

Enteric CH_4 emissions due to ruminal fermentation reflect a loss of diet energy; thus, it is important to reduce enteric methane emissions to promote sustainable economic development in this sector. Although there are opportunities to reduce the carbon impacts of livestock production throughout the supply chain, increasing productivity and feed efficiency are the best strategies for mitigating CH_4 emissions per unit of livestock product (Liu et al. 2017). There is empirical evidence from different studies that GHG emissions per unit of animal product are reduced by improving production efficiency and dietary composition (Caro et al. 2016; Chará et al., 2019). Increasing the nutrient quality of animal diets in silvopastoral systems results in the reduction of enteric CH_4 emissions per kg of dry matter intake (and per kg of product) (Barahona, 2014). Thornton and Herrero (2010) modeled potential measures to reduce GHG emissions in the tropics and estimated that the emissions per unit of milk and meat produced could be reduced by 57% and 73%, respectively, by replacing concentrates and part of the basal diet with *Leucaena leucocephala.*

The aforementioned results are indicative of considerable efforts to reduce the GHG emissions of grazing livestock systems in the tropics, including by simply improving grazing management (Picasso et al. 2014). Nevertheless, indiscriminate adoption of Tier-1 EFs over successive years has not enabled the capture of emission trends resulting from increasing productivity or changes in feeding practices (Lassey 2007). Changes in management practices by Mexican livestock producers must be adequately measured to facilitate the development and use of emission factors specific to tropical regions for the accurate calculation of methane emissions from enteric fermentation. This approach can increase the accuracy of farm and national carbon budgets, thereby reducing the uncertainty in assessing mitigation options that contribute to sustainable development at the farm and national levels (Ricci et al., 2013).

We found that the 2019 IPCC CH_4 EFs based on feed characteristics (such as the energy digestibility, neutral detergent fiber, and forage percentage) and animal productivity outperformed the 2006 IPCC EFs, as demonstrated by Benaouda et al. (2020). Likewise, we conclude that converting gross energy intake into enteric CH_4 emissions based on data specific to the Mexican tropics can improve the predictive capacity of the 2019 IPCC CH_4 EFs, such that the Tier-2MX methodology outperforms the Tier-2D methodology. Therefore, the 2019 IPCC emission factors developed using region-specific methane emissions data are recommended for use in national methane inventories of livestock in Mexico (Benaouda et al. 2020).

Our results show that it is critical to generate EFs specific to grazing cattle in the Mexican tropics because the Tier-1 emission factors proposed by the IPCC tend to overestimate methane emissions from enteric fermentation, particularly in grazing animals, as noted by Ricci et al. (2013). As cattle production in the Mexican tropics is characterized by grazing systems, developing region-specific emission factors could reduce the overestimation of emissions in national inventories.

4 Conclusions

Tier-2MX EFs for methane, which were estimated using a Y_m based on a methane yield specific to the Mexican tropics, were found to be lower than the default enteric EFs obtained using the Tier-1 methodology and the EFs estimated using the IPCC Tier-2D methodology. This result could be attributed to the default Y_m used in the Tier-2D methodology not being a realistic value for the Mexican tropics, as previously explained. Thus, it is important to generate information at the local level on which calculations of EFs and inventories can be based. The current uncertainty in reported national inventories would thereby be reduced, and mitigation practices for the livestock sector could be monitored.

The results show that food digestibility plays a determining role in enteric methane emissions. However, the percentage digestibility of foods assumed in this study is not specific to the Mexican tropics and may introduce uncertainty into the derived EFs. Therefore, the authors recommend that digestibility studies be carried out on food consumed by cattle in the Mexican tropics, including native vegetation, which is a primary livestock feed source in native silvopastoral systems.

Likewise, the productivity of livestock systems is concluded to influence the enteric methane emissions from cattle, because the NSP system (considered to be low-productivity) was found to produce higher methane emissions than the MC and ISP systems. Therefore, mitigation strategies for greenhouse gas emissions from livestock should focus on improving system productivity.

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Materials availability Not applicable.

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Declarations

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