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Article

Enteric Methane Emission Estimates for Cattle in Zambia from 1994-2022 Using the IPCC Tier 2 Approach

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Abstract

Agriculture is a significant contributor to greenhouse gas (GHG) emissions, with enteric methane (Ent_{CH₄}) from cattle production being a major source. In Zambia, cattle play a critical role in rural livelihoods and food security, yet the contribution of cattle production systems to national GHG emissions remains poorly quantified. This study employed the Intergovernmental Panel on Climate Change (IPCC) Tier 2 method to estimate Ent_{CH₄} from Zambia's cattle population from 1994 to 2022. The Tier 2 method offers a more accurate estimate than the Tier 1 method by incorporating country-specific data on cattle population demographics, husbandry, and feeding practices. The results highlight significant variations in Ent_{CH₄} over time, driven by changes in cattle population dynamics and production practices. This study underscored the importance of transitioning from the generalized Tier 1 to the Tier 2 method to capture the unique characteristics of Zambia's cattle production systems. The present findings provide critical insights for developing targeted mitigation strategies that will contribute to Zambia's ongoing efforts to address climate change while supporting sustainable livestock production.

Keywords: GHG emissions; cattle; ruminants; climate change; mitigation; Zambia

1. Introduction

The agriculture sector is of significant social, cultural, industrial and economic importance in the Southern Africa Development Community (SADC) region, contributing between 4% - 27% per cent of the agricultural domestic product (GDP). Over 70 per cent of the region's population, estimated to be slightly over 370 million, depends on agriculture for food, income and employment. Livestock production in the SADC region is significant, accounting for close to 40% of the agricultural domestic product in some countries (SADC, 2020). The livestock sector plays a pivotal role in food and nutritional security and is the economic backbone for some countries in the region. There is growing global and continental demand for livestock and livestock products. Hence, most of the countries in the region have embarked on livestock development plans to increase the livestock population and enhance value chain efficiency.

Cattle in the SADC region are regarded as one of the most important livestock species for their high economic returns and other contributions to both rural and urban economies. Hence, the performance of this sub-sector has a strong influence on food security, economic growth and social stability in the region. The cattle population in the region is estimated to be slightly over 85 million heads and has been growing rapidly by almost 2% in the last two decades (FAO, 2021). This growth

has been driven by an increase in demand for animal-sourced food (meat, milk) because of population growth, urbanization, the growing middle-income class and the attendant higher disposable income (Herrero et al., 2008; Enahoro et al., 2019 and Odubote, 2022).

Cattle are also a source of greenhouse gas (GHG) emissions, especially methane emissions, as a result of enteric fermentation. Ruminants produce methane as a by-product of the digestive process of enteric fermentation. Annual enteric methane emission is determined by the population size and by emissions per head per year, i.e., the emission factor. The emission factor varies with productive and reproductive performances, feed intake, and the type and quality of the feed basket. It is, thus, expected that the methane emissions from livestock will increase in response to the growing demand for animal-sourced food in the SADC region and efforts to increase productivity.

Livestock plays a crucial role in Zambia's economy, contributing to food security, employment generation, and poverty alleviation. The livestock sub-sector contributes 3.2% and 42% to the national and agriculture sector GDP. Therefore, it has the potential to deliver both agricultural-led growth and socio-economic transformation as aspired to in the Eight National Development Plan (8NDP) and Vision 2030 (DLD, 2024). Among livestock, cattle are significant, providing meat, milk, draft power, and manure for smallholder farmers (Mumba et al., 2018). Cattle also play a cultural role in many Zambian communities, serving as a source of wealth, status, and social security (Mumba et al., 2018). With a cattle population of 5,115,495 heads (DLD 2024), livestock is a significant source of greenhouse gas (GHG) emissions.

Enteric fermentation is a key category in the cattle GHG inventory, and the IPCC Guidelines recommend that it is quantified using a Tier 2 method for major emitting species, such as cattle. The Tier 2 method is also more useful than the Tier 1 method for assessing the effects of livestock sector trends and policy measures on GHG emissions. It can better reflect actual practices and animal performance in the country. The development of a Tier 2 GHG inventory is expected to support further identification of livestock GHG mitigation options in line with national development and adaptation priorities.

According to Zambia's first Biennial Update Report (BUR, 2020) to the United Nations Framework Convention on Climate Change (UNFCCC), enteric fermentation using the Tier 1 method contributed about 4,200 Gg CO₂e, or 27% of agricultural GHG emissions, with further emissions from dung and urine deposited on pasture. Livestock GHG emissions are therefore expected to increase with further development of the sector. Using the Intergovernmental Panel on Climate Change (IPCC) Tier 1 method, Zambia's latest GHG inventory (GRZ 2020) indicates that enteric methane is the largest source of cattle emissions and a key emission source in the national inventory. Enteric methane thus requires a more accurate estimation to identify mitigation strategies. The IPCC Tier 1 method commonly used for emission estimation applies standard continental emission factors that are unable to account for the diversity of production systems and agroecological conditions, such as those present in Zambia. This has led to a growing need for more precise assessments using the IPCC Tier 2 approach, which incorporates country-specific data on feed intake, livestock productivity, and management practices (Graham et al., 2022).

Zambia, in its National Determined Contributions (NDC), has indicated its interest in and commitment to reducing emissions associated with the livestock sector (Ministry of Green Economy and Environment, 2023). There has, however, been limited previous research on livestock GHG emissions in Zambia, similar to a number of other sub-Saharan countries (Graham et al. 2022). Most countries have been using the less accurate IPCC Tier 1 approach to estimate livestock emissions in their national inventories (Wassie et al., 2022).

This study addresses this critical gap by applying the Tier 2 method to estimate enteric methane (Ent_{CH4}) emissions from Zambia's cattle population over nearly three decades (1994–2022). By leveraging detailed data on cattle demographics, production systems, and feeding practices, the present study provides a more accurate emissions profile for the cattle production sector. The findings will inform future priorities for research, as well as sustainable livestock policies aligned with Zambia's climate change mitigation efforts.

2. Materials and Methods

Estimates of EntCH₄ emissions were generated using the Tier 2 method described in the IPCC (2006) guidelines and the 2019 *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019). Dairy cattle were categorized following the OIE (2021) guidelines, which defined dairy cattle production systems as commercial systems where the purpose of the operation includes some or all of the breeding, rearing and management of cattle intended for the production of milk. This included purebred dairy exotics and their crossbreds. Other cattle refers to indigenous breeds and exotic purebred beef cattle, including their crossbreds, that are mostly kept for beef or multiple purposes (i.e., beef, milk and draught power).

2.1. Cattle Production Systems in Zambia

Cattle production in Zambia is characterized by a diversity of systems shaped by agroecological zones, cultural practices, farmers' production objectives and management practices, available natural resources, use of breeding and assisted reproductive technology, and access to markets (Mumba et al., 2017; Odubote, 2022). These production systems are distributed across Zambia's diverse agroecological zones, with cattle populations concentrated in regions such as Western, Eastern, Southern, and Central Provinces (Mumba et al., 2018). Each region presents unique opportunities and challenges, including variations in rainfall, grazing resources, and vulnerability to climate change impacts such as droughts and flooding (Mumba et al., 2024).

The majority of cattle in Zambia are raised in traditional or extensive systems, predominantly managed by smallholder farmers (Sinkala et al., 2014). These systems rely heavily on natural pastures and communal grazing, with minimal inputs such as supplementary feeding, veterinary care, or improved breeding practices. Although these systems provide critical livelihood resources for many rural households, they are often characterized by low productivity, prolonged calving intervals, and high mortality rates (Mumba et al., 2018). Cattle in these systems typically consume low-quality feed, which may lead to higher methane (CH₄) emissions per day and per unit of livestock product (Ouatahar et al., 2021).

Semi-intensive systems represent a transition between traditional and commercial production. Farmers in these systems often adopt some improved management practices, such as controlled grazing, supplementary feeding, and basic veterinary care (Mumba, 2012). These systems are more prevalent in peri-urban areas and regions with better market access. While productivity is higher compared to traditional systems, semi-intensive systems still face challenges, including feed availability and climate variability. Commercial cattle production in Zambia is classified as an intensive system, with significant investments in infrastructure, feed quality, and animal health. These systems primarily focus on dairy and beef production for domestic and export markets (Mumba et al., 2018). High-quality feed and modern management practices contribute to increased productivity and reduced CH₄ emissions per unit of product. However, commercial systems account for a small proportion of the national cattle population due to the high capital and operational costs involved.

In this study, five cattle production systems were identified, namely commercial dairy, emergent dairy, commercial beef, emergent beef and extensive (i.e., traditional or transhumant systems) beef. The commercial dairy and beef production systems are mostly found along the railway tracks, while the extensive and emergent systems are located in the rural agricultural and peri-urban areas, respectively.

2.2. Defining and Sub-Categorizing Cattle Production Systems

The IPCC (2006) recommends that cattle populations should be classified into at least three main subcategories: mature cows, other mature cattle, and growing cattle. However, depending on the level of detail in the emission estimation method, subcategories could be further classified based on animal age, sex or feeding systems. The classification in the present study reflected cattle type (dairy,

other), feed characteristics (production system) and animal characteristics (age, sex). Accordingly, five subcategories (Adult cows > 3 years, Adult males > 3 years, Heifers 1-3 years, Steers/Bulls 1-3 years, Calves < 1 year) were identified in each of the five cattle production systems. In addition, the commercial and extensive/traditional production systems had feedlot cattle and oxen, respectively, which were included as extra subcategories. Thus, there are ten dairy cattle subcategories and 17 other cattle subcategories (Table 1).

Table 1. Cattle subcategories for the different cattle production systems in Zambia.

Livestock category	Production system	Animal subcategories
Dairy	Commercial dairy system	Adult cows (> 3 years)
		Adult males (> 3 years)
		Heifers (1-3 years)
		Steers/Bulls (1-3 years)
		Calves (< 1 year)
	Emergent dairy system	Adult cows (> 3 years)
		Adult males (> 3 years)
		Heifers (1-3 years)
		Steers/Bulls (1-3 years)
		Calves (< 1 year)
Other cattle	Commercial beef	Adult cows (> 3 years)
		Adult males (> 3 years)
		Heifers (1-3 years)
		Steers/Bulls (1-3 years)
		Calves (< 1 year)
	Emergent beef	Feedlot (91 days)
		Adult cows (> 3 years)
		Adult males (> 3 years)
		Heifers (1-3 years)
		Steers/Bulls (1-3 years)
	Extensive/ Traditional beef	Calves (< 1 year)
		Adult cows (> 3 years)
		Adult males (> 3 years)
		Oxen (> 3 years)
		Heifers (1-3 years)
		Steers/Bulls (1-3 years)
		Calves (< 1 year)

2.3. Data Collection

Ent_{CH4} emissions were estimated for each year in the period from 1994 to 2022. Livestock activity data, including population, animal performance (i.e., milk yield, weight), and feed basket composition for the different cattle subcategories, were obtained from country-specific data sources through systematic web searches using Google Scholar and bibliographic references. Literature reports that were conducted on cattle starting from 1994 (the base year for Zambia's national inventory) were utilized for the present study if they reported parameter values relating to one or more of these variables: herd structure, production system, breed, live weight (LW), weaning LW, mature LW, LW gain, calving rate, calving interval, lactation length, milk yield, milk fat and protein contents, feed basket composition and nutritional quality (including metabolizable energy, digestible energy (DE)), and hours of work (i.e., draught power). All available reports were pooled to support time series consistency. This study was implemented using only secondary data.

After compiling available literature reports, data gaps such as missing data and data inconsistencies were identified. To fill in data gaps from the literature review, an expert judgement workshop was convened with a knowledgeable team of 14 technical experts with over 15 years of experience in the field and several publications. The experts who were part of the project advisory group were carefully drawn from the Ministry of Fisheries and Livestock, academia, NGOs and the private sector. They were required to provide anonymized responses from their wealth of experience and literature on animal performance, manure management, and feed basket composition to generate consensus on country-specific data for each livestock parameter. The responses were consolidated and then debated at an in-person and in-house workshop held in August 2022, where the values were unanimously agreed upon before being accepted.

2.4. Cattle Subcategories (Herd Structure) and Population Data

The input data to estimate cattle populations for each year were obtained from the FAOSTAT database. The FAOSTAT database made use of national official data (such as the 2017/2018 Livestock and Aquaculture Census and 2022 Livestock Survey) and estimates based on FAOSTAT imputation methodology (FAOSTAT, 2022). From the FAOSTAT dataset, the dairy cattle population was calculated to be an average of 9% of the total population, while other cattle represented 91%. There was no official data source on the disaggregated dairy cattle sub-categories in Zambia. For this initial inventory, we assumed commercial dairy populations for the period 1994 – 2022 to be 25% of the total dairy cattle population based on expert judgment. The remaining 75% was assumed to be the emergent dairy cattle population. For other cattle, we assumed 14.5%, 6.2%, and 79.3% of the total other cattle population to be commercial beef, emergent beef, and traditional/extensive beef populations for the period 1994 – 2022, which was also based on expert judgment. The cattle population estimates disaggregated by cattle type for 2021 and 2022 were obtained by linear extrapolation according to the method suggested by Pica-Ciamarra et al. (2014). The total cattle population by cattle type and by production system is shown in Table 2.

Table 2. Time series for the overall cattle population by cattle type and production system (head).

Year	Commercial dairy	Emergent dairy	Total dairy cattle Population	Commercial beef	Emergent beef	Traditional beef	Total beef cattle population	Total cattle population
1994	61181	183544	244725	338615	144785	1851873	2335273	2579998
1995	67500	202500	270000	308851	132060	1689091	2130002	2400002
1996	63000	189000	252000	282460	120776	1544765	1948001	2200001
1997	47251	141751	189002	364169	155715	1991633	2511517	2700519
1998	49000	147000	196000	369920	158173	2023083	2551176	2747176
1999	52500	157500	210000	390758	167083	2137040	2694881	2904881
2000	62500	187500	250000	343793	147001	1880193	2370987	2620987
2001	65000	195000	260000	353800	151280	1934920	2440000	2700000
2002	70000	210000	280000	324443	138727	1774377	2237547	2517547
2003	70000	210000	280000	303843	129918	1661710	2095471	2375471
2004	67500	202500	270000	300435	128461	1643073	2071969	2341969
2005	70000	210000	280000	331580	141778	1813397	2286755	2566755
2006	67500	202500	270000	366843	156858	2006261	2529962	2799962
2007	70000	210000	280000	315747	135008	1726807	2177562	2457562
2008	71251	213751	285002	294399	125881	1610049	2030329	2315331
2009	72500	217500	290000	398460	170376	2179165	2748001	3038001
2010	73751	221251	295002	406726	173910	2224366	2805002	3100004
2011	73751	221251	295002	325495	139177	1780123	2244795	2539797
2012	73751	221251	295002	525931	224882	2876297	3627110	3922112
2013	73751	221251	295002	541091	231364	2959205	3731660	4026662
2014	75000	225000	300000	548826	234670	3001506	3785002	4085002
2015	68751	206251	275002	532345	227624	2911378	3671347	3946349
2016	67500	202500	270000	510873	218442	2793948	3523263	3793263
2017	71251	213751	285002	502873	213157	2750187	3466217	3751219

2018	69166	207500	276666	498510	211965	2726334	3436809	3713475
2019	69304	207916	277220	495723	214573	2711100	3421396	3698616
2020	69908	209722	279630	501822	217180	2744449	3463451	3743081
2021	70510	211528	282038	507920	219785	2777798	3505503	3787541
2022	105726	317180	422906	620029	265117	3390919	4276065	4698971

The population of cattle in each subcategory was estimated using the herd structure shown in Supplementary Tables S1a and b. Given the lack of data on changes in herd structure over time, the herd structure proportions for each subcategory were assumed to be constant and hence were applied throughout the time series (from 1994 to 2022). Supplementary Tables S2a and b show the dairy and other cattle subcategory populations.

2.5. Liveweight and Weight Gain

There is a paucity of information on the LW and mature LW of both dairy and other cattle since only a few published studies provided the data utilized. This informed the expert judgement session to address the gaps in the available data. For adult cows, LW was calculated as the total average LW of adult cows from articles/reports reporting LW for female animals, followed by expert judgment sessions after discarding outliers to ensure less than 20% coefficient of variation. For adult bulls, LW was estimated using expert judgement sessions as there were no reports on this category. For calves 0–1 year old, the median age in this subcategory was set at six months, and the expert judgment panel estimated the LW at six months. For heifers and growing male cattle (1-3 years), the median age was 24 months, and the expert judgment panel estimated the LW. Given the lack of data on live weights over time, the values calculated for each subcategory in the dairy and other production systems were assumed to be constant and were applied throughout the time series data (from 1994 to 2022).

The LW gain for adult cows and bulls was assumed to be zero, which is consistent with the IPCC (2006) guidelines. LW gains for heifers (1-3 years) and growing males (1-3 years) were estimated based on the following methods. To ensure consistency with the LW data used, the average daily LW gain for each subcategory was calculated by dividing the change in LW between two age classes by the number of days between the median age of each age class. For instance, LW gain for heifers and growing males was calculated as the difference between the LW of the growing heifers or growing males (1-3 years) and the live weight of the calves (0-1 year) was divided by the difference between the median age (in days) of the growing heifers or growing males (assuming 24 months as median age: 24 x 30.4 days = 730 days) and the median age (in days) of the calves (assuming a median age of 6 months: 6 x 30.4 days = 182 days). The weight gain for calves (0-1 year) was calculated as the difference between the live weight of calves (0-1 year) and the live weight of the calves at birth, divided by the median age (in days) of the calves (assuming a median age of 6 months: 6 x 30.4 days = 180 days). Given the lack of data on changes in weight gain over time, the values estimated for each subcategory of the dairy and other production systems were assumed to be constant and hence were applied throughout the time series data (from 1994 to 2022) and are shown in Supplementary Table S3.

2.6. Proportions of Females Giving Birth, Milk Yield and Milk Fat

The proportion of cows giving birth was estimated directly from calving rates as a proxy indicator:

$$P = (\text{total number of calves} / \text{number of cows exposed to bulls}) * 100$$

The calving rate is defined as the proportion of cows giving birth (P) out of the total number of cows exposed to bulls during the breeding season. Estimates less than 50% were removed from the analysis of average calving rates. For other cattle, due to limited available data in the literature, expert judgement was used to determine the proportion of cows giving birth. The proportions of cows giving birth (calving rate) in the commercial and emergent dairy systems were estimated at constant values of 73.8% and 63.7%, respectively. For other cattle, they were estimated at constant values of

80%, 59.1% and 55% for commercial beef, emergent beef and traditional/extensive production systems, respectively. These estimates were consistently used throughout the times series.

Milk yield estimates for the commercial dairy production system were obtained from various reports across the country (Neven et al., 2006; World Bank, 2011; MAL, 2012; ACF, 2012; SNV, 2013; Kawambwa et al., 2014; ZEMA, 2020, SAIPR, 2019, Mumba, 2020, SIDA, 2020, ZAMBEEF, 2022). These were mostly from survey records of milk off-take (i.e., volume of milk obtained by milking). These milk yields were categorized into two time periods: 2006 and 2011 (with the mean year of 2009 and average daily milk yield of 17.0 litres/day) and studies spanning from 2012 to 2022 (with the mean year of 2017, and average daily milk yield of 21.3 litres/day). After collating literature reports, the estimated daily milk off-take was converted to an annual average daily off-take (i.e., over 365 days) by multiplying the calculated average daily milk off-take by lactation duration and the proportion of cows giving birth. For instance, for the year 2009, $17.0 \times (275 \text{ day}/365 \text{ days}) \times 0.738 = 9.5 \text{ kg}$ (or 9.8 l) per cow per day, and for the year 2017, $21.3 \times (275/365 \text{ days}) \times 0.738 = 11.8 \text{ kg}$ (or 12.2 l) per cow per day for the commercial dairy production system. Extrapolation was used to estimate milk yield for the period between 1994-2008 and 2018-2022, and interpolation was used for the years between 2009-2017 based on the average values for 2009 and 2017 (reference years). The reference years were determined by taking the average of the years for which data was available. For lactation length, the simple average of all the literature review articles/reports was used, i.e., 275 days. Given the lack of data on changes in lactation length and milk fat content over time, the simple average values were assumed to be constant and hence were applied throughout the time series data (from 1994 to 2022).

Similarly, milk yield estimates for emergent dairy production systems were obtained from various reports by Neven et al. (2006), World Bank (2011), MAL, (2012), ACF (2012), SNV (2013), Kawambwa et al. (2014), Hofer (2015), ZEMA (2018), Ledgard et al. (2018), SAIPR (2019), SIDA (2020), Mumba (2020), GIZ (2021), ZNS (2022), Odubote et al (2022), ZDTP (2022), and GIZ (2022). To determine the average daily milk yield per head in the emergent dairy production system, three data points, namely 1998, 2011 and 2022, were defined. Mean values were determined for values falling between 1994-1998, 1999-2011 and 2012-2022, and these were applied for the intervening years. For the other cattle type, a constant value of 3.7 kg and 2.0 kg average milk yield were applied for the emergent beef and traditional beef for the entire time series from 1994 to 2022, as presented in Supplementary Table S4. A default value of 3.5% was used for milk fat content for all cows, following IPCC guidelines (IPCC, 2006).

2.7. Work Hours for Oxen

Oxen in the extensive traditional production system are used for draught power (Mumba et al. 2018). They are mainly used for ploughing and transportation of crop produce, food commodities, firewood, and water. The average work hours for oxen are 3.5 hours per day for 46 days in the ploughing season (Bars and Zwart 1996). Oxen are also used for an average of 50 days per year for transportation. To calculate the average hours worked per day by oxen, we multiplied the days worked by hours worked per day in all activities and divided them by 365 days (year). The total hours worked per calendar day was 0.715 hours per oxen per year.

2.8. Diet Composition and Feed Characteristics

An expert judgement panel was used to define diet components and characterize feed characteristics in the dairy and other cattle production systems since there was no published literature data. With the help of a questionnaire, the experts were asked individually to categorize the available diet components. They listed seven feed categories: 1) natural forages (i.e., grazing on unimproved or improved and/or cut-and-carry system), 2) planted pastures or forages (i.e., grass or legumes or fodder shrub/tree species), 3) grass hay (cut-and-carry system), 4) silage (i.e., maize, elephant grass etc.), 5) agro-industrial by-products (e.g., oil seedcakes, cereal milling by-products, molasses, brewers' waste etc.), 6) concentrates and supplements (i.e., commercial, or home-made, mineral

supplements), 7) crop residues (i.e., from agricultural fields, households, marketplaces, food processing etc.). The diet composition, as determined by the expert panel, is shown in Supplementary Table S5.

2.9. Other Coefficients in the IPCC Tier 2 Method

IPCC (2006) gives the coefficients for maintenance (C_f) default values for lactating cows as 0.386, for non-lactating cows, growing cattle, and oxen as 0.322 and for bulls as 0.37. Country specific values for C_f were, however, weighted for dairy cows and other cows by the proportion of dairy cows giving birth in the herd and the lactation period. For adult males (i.e., bulls), the value of C_f was 0.370 across production systems and 0.322 for non-lactating cows, growing animals, and oxen.

2.10. Gross Energy Intake Estimation

The list of common cattle feedstuffs available in Zambia with their respective chemical compositions and nutritive values, including dry matter (DM), crude protein (CP) and metabolizable energy (ME), was generated from the literature review. In the IPCC Tier 2 method, the amount consumed is predicted based on gross energy requirements, which depends on diet digestibility and animal performance, so data on the amounts of specific feedstuffs consumed by cattle is not needed. Feed energy digestibility (DE%) values of each feedstuff were estimated using the following two equations from CSIRO (2007):

$$\text{Feed energy digestibility (DE, \%)} = \text{Digestible energy (DE, MJ)} / 18.4 \tag{1}$$

$$\text{Digestible energy (DE, MJ)} = \text{Metabolizable energy (ME MJ)} / 0.81 \tag{2}$$

The final DE (%) value for each animal subcategory was calculated as the weighted sum of the individual feedstuffs' DE values and their corresponding proportions in the feed basket. The resulting estimates were 61%, 61.2% and 61.4% for commercial dairy and 58.1%, 58.2% and 58.0% for emergent dairy for the years 1995, 2007 and 2021, respectively. For beef cattle, 56%, 54.4% and 53.7% were used for the respective and intervening years.

2.11. Enteric Methane Emission Factors

The enteric methane emission factors were calculated for each cattle subcategory in each production system using the IPCC (2006) equation.

$$EF = (GE \times (Y_m / 100) \times 365 \text{ days}) / 55.65 \tag{3}$$

Where EF = the emission factor (kg CH₄/head/year), GE = gross energy intake (MJ/head per day), Y_m = CH₄ conversion factor (%), 55.65 (MJ/kg CH₄) = energy content of CH₄, 365 days = number of days in the year. The value for the methane conversion factor used was the IPCC (2019) default value of 6.5% for all cattle production systems, except for the extensive/traditional production system for which the default value of 7.0% was applied. For calves, a methane conversion factor of 3.25% was used because the average calf is only alive for 6 months in the year, representing emissions after weaning at the age of 90 days and no emissions during the 90 day suckling period.

2.12. Uncertainty Analysis

Uncertainty analysis for enteric methane emission was accomplished by Monte Carlo simulation implemented in Palisade @Risk software using the inventory mean values, margins of error around the mean value, and assumed probability density functions for each input parameter. The contribution of each variable to total uncertainty was estimated using Spearman's ranked correlation coefficients (Milne et al., 2014). The uncertainty of cattle populations was estimated based on the difference between FAOSTAT estimates for 2022 and the results of the 2022 Livestock Survey (MoFL and ZAMSTAT 2022). For standard coefficients used in the IPCC Tier 2 equations, margins of error and probability density functions were chosen with consideration of prior literature (Monni et al.,

2007; Karimi-Zindashty et al., 2012; Milne et al., 2014). For country-specific parameters, margins of error were calculated from the datasets used to estimate parameter values, where available. In the case of parameters estimated using expert judgement, a triangular distribution was assumed. Expert judgement was used to estimate minimum and maximum likely values, with the inventory value as the most likely value.

Our inventory estimated a 2022 population of 3.24 million cattle in both emergent and traditional beef production systems, compared to 4.41 million in the 2022 Livestock Survey (MoFL and ZAMSTAT 2022) and 0.59 million in the commercial sector compared to 0.29 million in the survey. These represent differences of 36% and 50%, respectively. The livestock survey report did not give specific data on herd structure for the commercial dairy and beef production systems. So, a margin of error of $\pm 50\%$ was assumed for all animal subcategories in 2022. The margins of error and probability density function (pdfs) used for Y_m (methane conversion factor), cfi (coefficient for net energy for maintenance), LW (live weight) and Ca (coefficient for net energy for activity) in the uncertainty analysis are presented in Supplementary Table S6. For both emergent and traditional beef production systems (i.e., emergent dairy and beef and extensive systems), variation between predicted inventory values and survey values differed between cattle subcategories. They ranged between 17.7% and 58.5% (Supplementary Table S7). The total population estimated in the 2022 survey was 21% higher than the total population in the inventory. Therefore, for 1994, we assumed that the uncertainty of individual subcategory populations could be up to two times higher, i.e. $\pm 42\%$, which was applied to all animal subcategories.

3. Results

3.1. Cattle Population

The cattle population was found to have increased by 82.1% from 2,579,998 heads in 1994 to 4,698,971 heads in 2022 (MFL, 2023), and enteric methane emissions also increased by 81.9% from 165.0 to 300.2 Gg CH_4 /year for the same period. The rapid growth in the cattle population could be attributed to the government livestock development policy in the last two decades, coupled with generally good rainfall patterns necessary for grazing and rangelands (Odubote, 2022). The growth rate over the whole period is comparable to that of sub-Saharan Africa (75.8%) and developing countries as a whole (81.2%) (FAO 2022).

3.2. Trends and Sources of Total Emissions

The total enteric CH_4 emission from Zambia cattle increased from 165 Gg CH_4 in 1994 to 300.2 Gg CH_4 in 2022 (Table 3). The undulating figures for methane emissions from enteric fermentation are due to changing cattle population mainly associated with disease outbreaks such as Foot and Mouth Disease, Contagious Bovine Pleural Pneumonia and East Coast Fever from 2000-2005 (Sinkala, 2014) due to the drought caused by El Nino in 2015/2016 Agricultural season, and Government interventions through stocking and restocking programmes in 2006-2010. The average contributions of dairy cattle and other cattle to the total methane emissions from cattle between 1994-2022 were 9 and 91 %, respectively. Figure 1 shows the cattle population and total methane emission trend over the time series. Other cattle in the extensive traditional production system made the largest contribution to the yearly enteric CH_4 emissions, accounting for an average of 72.5% of total enteric emissions, followed by the commercial beef production system (annual average of 14.3%). Dairy cattle from commercial and emergent dairy production systems, on average, contributed annually, 2.7% and 5.9%, respectively, of the total emissions.

Table 3. Methane emissions from enteric fermentation for various cattle production systems in Zambia, 1994 - 2022 (Gg methane).

Year	Commercial dairy farm	Emergent dairy farm	Commercial beef	Emergent beef	Extensive/traditional	Total
1994	4.2	10.1	22.4	7.8	120.4	165.0
1995	4.6	11.2	20.6	7.1	109.9	153.4
1996	4.4	10.4	18.9	6.5	100.5	140.7
1997	3.3	7.8	24.5	8.3	129.5	173.5
1998	3.5	8.1	25.0	8.4	131.6	176.6
1999	3.8	8.7	26.5	8.8	139.0	186.8
2000	4.5	10.4	23.4	7.7	122.3	168.3
2001	4.7	10.8	24.2	7.9	125.8	173.5
2002	5.1	11.6	22.3	7.2	115.4	161.7
2003	5.2	11.6	21.0	6.8	108.1	152.6
2004	5.0	11.2	20.9	6.7	106.9	150.6
2005	5.3	11.6	23.1	7.3	117.9	165.3
2006	5.1	11.2	25.7	8.1	130.5	180.6
2007	5.4	11.6	22.2	6.9	112.3	158.4
2008	5.5	11.8	20.7	6.5	104.5	149.0
2009	5.7	12.0	28.1	8.7	141.2	195.7
2010	5.8	12.3	28.7	8.9	143.8	199.5
2011	5.9	12.3	23.0	7.1	114.9	163.1
2012	5.9	12.3	37.3	11.5	185.3	252.2
2013	6.0	12.3	38.4	11.8	190.3	258.7
2014	6.1	12.5	39.0	12.0	192.6	262.2
2015	5.6	11.5	37.9	11.6	186.5	253.1
2016	5.6	11.3	36.5	11.1	178.6	243.1
2017	5.9	11.9	36.0	11.0	175.5	240.2
2018	5.8	11.6	35.7	10.9	173.6	237.5
2019	5.9	11.6	35.6	10.8	172.3	236.3
2020	6.0	11.7	36.1	10.9	174.1	239.0
2021	6.1	11.8	36.6	11.1	176.2	241.9
2022	6.2	11.9	37.0	11.2	178.3	300.2

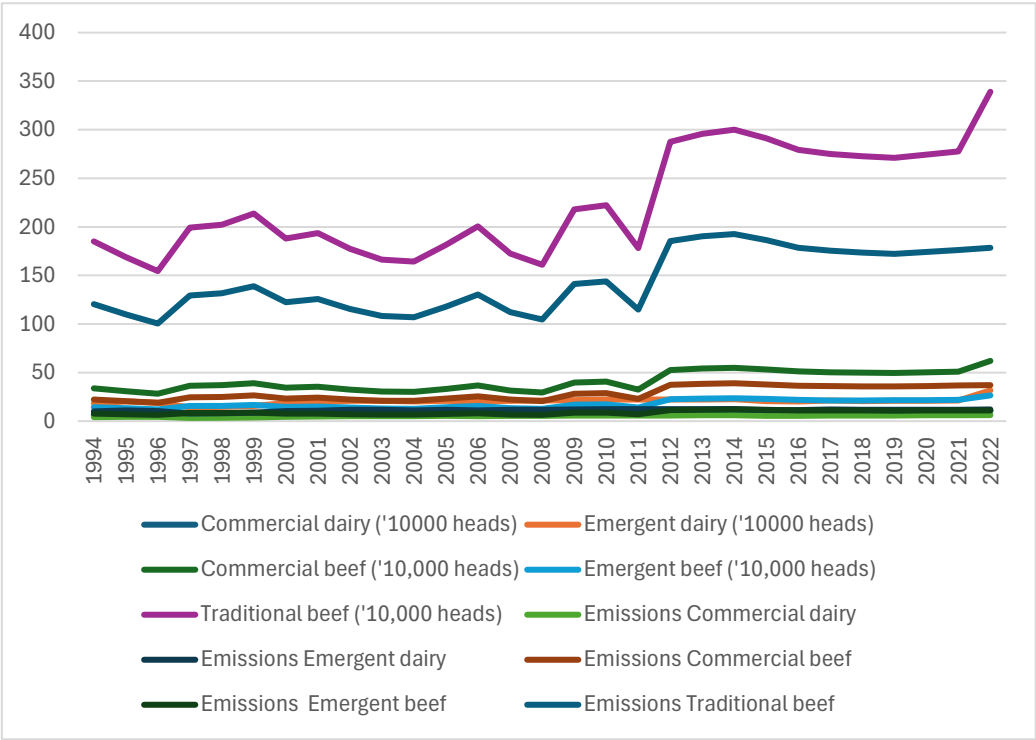


Figure 1. Cattle population and total emission trends from 1994-2022 .

3.3. Emission Factors

The calculated methane emission factors for dairy and other cattle in Zambia are presented in Tables 4a and b. The mean methane emission factors for commercial dairy ranged from an average of 17.8 kg CH₄ head/year for calves to 99 kg CH₄/head/year for adult cows and an average of 18.7 kg CH₄ /head/year for calves in the emergent dairy to 70.5 kg CH₄ /head/year. The same trend could be observed for the other cattle, except that the emission factors were lower in each age/sex class. Generally, adult cows and heifers had higher enteric methane emission factors than adult males and steers, respectively, for both cattle types and the five production systems. Calves had the lowest enteric methane emission factors. It was also noted that the enteric methane emission factors generally increased from 1994 to 2022 for all production systems except for the emergent beef and extensive traditional production systems. The average emission factor for the adult cows from 1994 to 2022 for commercial dairy, emergent dairy, commercial beef, emergent beef and traditional beef production systems were 99.1, 70.5, 96.8, 74.3 and 72.9 kg CH₄/head/year, respectively.

The resulting implied emission factors (IEF) (i.e., population-weighted average emission factors) for both dairy and other cattle in the various production systems are presented in Tables 4a and b. The IEFs for the dairy cattle commercial and emergent production systems, 77.4 and 55.4 kg CH₄ /head/year, were generally higher than for the other cattle commercial and emergent production systems, 69.8 and 51.9 kg CH₄ /head/year, respectively. The IEFs for dairy cattle in the commercial and emergent systems increased from 68.2 kg CH₄/head/year to 86.7 kg CH₄/head/year and from 55.2 kg CH₄/head/year to 55.9 kg CH₄/head/year from 1994 to 2022, respectively. For other cattle, the extensive traditional beef production system recorded a decrease from 65.0 kg CH₄/head/year in 1994 to 63.4 kg CH₄/head/year in 2022 for the IEF. However, the commercial beef cattle production system recorded an increase in the IEF from 66.3 kg CH₄/head/year in 1994 to 72.0 kg CH₄/head/year in 2022.

3.4. Uncertainty

Monte Carlo simulation estimated a total uncertainty for cattle populations of about ±16% in 2022 and ±19% in 1994. Regression coefficients indicated that the subcategory populations with the most significant influence on total population uncertainty were all in the extensive beef and commercial beef systems. The uncertainty of the implied emission factor (IEF) for 2022 was estimated at (+12.8%, -11.7%). The top factors driving uncertainty of the IEF for all cattle in 2022 are Y_m, C_{fi}, digestibility and live weight for cows in the extensive beef system. Other influential variables were Y_m, C_{fi}, and LW for extensive oxen, Y_m for commercial beef cows and extensive system heifers, and Ca for extensive system cows. Populations of calves, oxen, and heifers in the extensive system, as well as commercial beef cows, also influence the IEF.

Overall, the results of uncertainty analysis indicate that to reduce the uncertainty of the Tier 2 cattle inventory, better population subcategory estimates are required in the extensive and commercial beef systems, and better data is required on feed digestibility, live weights and grazing distances in the extensive and commercial beef systems.

Table 4a: Enteric methane emission factors for dairy cattle subcategories in Zambia 1994-2022 (kg CH₄ head⁻¹ year⁻¹).

	Commercial dairy system						Emergent dairy system					
	Adult cows	Adult males	Heifers	Steers/bulls	Calves	Implied emission factor	Adult cows	Adult males	Heifers	Steers/bulls	Calves	Implied emission factor
1994	83.5	61.3	48.4	47.5	17.9	68.2	70.0	60.2	51.8	48.7	18.3	55.2
1995	84.6	61.3	48.4	47.5	17.9	68.9	70.1	60.2	51.8	48.7	18.3	55.2
1996	85.7	61.3	48.4	47.4	17.9	69.5	70.1	60.2	51.8	48.6	18.3	55.2
1997	86.9	61.2	48.3	47.4	17.9	70.2	70.1	60.2	51.8	48.6	18.2	55.2
1998	88.0	61.2	48.3	47.4	17.9	70.9	70.1	60.2	51.7	48.6	18.2	55.2
1999	89.1	61.2	48.3	47.4	17.9	71.5	70.1	60.2	51.7	48.6	18.2	55.3
2000	90.2	61.2	48.3	47.4	17.9	72.2	70.1	60.2	51.7	48.6	18.2	55.2
2001	91.3	61.1	48.2	47.3	17.9	72.8	70.2	60.2	51.7	48.6	18.2	55.2

2002	92.4	61.1	48.2	47.3	17.9	73.5	70.2	60.1	51.7	48.6	18.2	55.2
2003	93.5	61.1	48.2	47.3	17.9	74.2	70.2	60.1	51.7	48.6	18.2	55.2
2004	94.7	61.1	48.2	47.3	17.9	74.8	70.2	60.1	51.7	48.5	18.2	55.2
2005	95.8	61.1	48.2	47.3	17.9	75.5	70.2	60.1	51.7	48.5	18.2	55.3
2006	96.9	61.0	48.1	47.2	17.9	76.1	70.2	60.1	51.6	48.5	18.2	55.3
2007	98.0	61.0	48.1	47.2	17.8	76.8	70.3	60.1	51.6	48.5	18.2	55.3
2008	99.1	61.0	48.1	47.2	17.8	77.5	70.3	60.1	51.6	48.5	18.2	55.3
2009	100.2	61.0	48.1	47.2	17.8	78.1	70.4	60.1	51.7	48.5	18.2	55.3
2010	101.3	61.0	48.1	47.2	17.8	78.8	70.4	60.1	51.7	48.6	18.2	55.4
2011	102.4	60.9	48.1	47.1	17.8	79.4	70.5	60.2	51.7	48.6	18.2	55.4
2012	103.5	60.9	48.0	47.1	17.8	80.1	70.6	60.2	51.7	48.6	18.2	55.5
2013	104.6	60.9	48.0	47.1	17.8	80.7	70.6	60.2	51.8	48.6	18.3	55.5
2014	105.8	60.9	48.0	47.1	17.8	81.4	70.7	60.2	51.8	48.7	18.3	55.5
2015	106.9	60.9	48.0	47.1	17.8	82.1	70.7	60.3	51.8	48.7	18.3	55.6
2016	108.0	60.8	48.0	47.1	17.8	82.7	70.8	60.3	51.8	48.7	18.3	55.6
2017	109.1	60.8	47.9	47.0	17.8	83.4	70.9	60.3	51.9	48.7	18.3	55.7
2018	110.2	60.8	47.9	47.0	17.8	84.0	70.9	60.3	51.9	48.7	18.3	55.7
2019	111.3	60.8	47.9	47.0	17.8	84.7	71.0	60.3	51.9	48.8	18.3	55.7
2020	112.4	60.8	47.9	47.0	17.8	85.4	71.0	60.4	51.9	48.8	18.3	55.8
2021	113.5	60.7	47.9	47.0	17.8	86.0	71.1	60.4	52.0	48.8	18.3	55.8
2022	114.6	60.7	47.9	47.0	17.7	86.7	71.2	60.4	52.0	48.8	18.3	55.9
Mean	99.1±9.1	61.0±0.2	48.1±0.2	47.2±0.1	17.8±0.1	77.4±5.4	70.5±0.4	60.2±0.1	51.8±0.1	48.6±0.1	18.3±0.0	55.4±0.2

Table 4b: Enteric methane emission factors for other cattle subcategories in Zambia 1994-2022 (kg CH₄ head⁻¹ year⁻¹).

	Commercial beef							Emergent							Extensive/traditional beef						
	Adult cows	Adult males	Heifers	Steers/bulls	Calves	Feedlot	Implied emission factor	Adult cows	Adult males	Heifers	Steers/bulls	Calves	Implied emission factor	Adult cows	Adult males	Oxen	Heifers	Steers/bulls	Calves	Implied emission factor	
1994	92.4	67.5	44.9	49.3	46.0	40.9	66.3	77.5	68.3	36.4	38.5	18.5	54.1	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
1995	92.7	67.8	45.1	49.6	46.3	41.1	66.6	77.1	68.0	36.2	38.3	18.4	53.9	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
1996	93.1	68.1	45.3	49.8	46.6	41.4	66.9	76.8	67.7	36.0	38.1	18.3	53.6	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
1997	93.5	68.4	45.5	50.0	46.9	41.6	67.2	76.5	67.4	35.8	38.0	18.2	53.4	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
1998	93.9	68.7	45.7	50.3	47.1	41.8	67.5	76.2	67.2	35.7	37.8	18.1	53.	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
1999	94.3	69.0	46.0	50.5	47.4	42.1	67.8	75.8	66.9	35.5	37.6	18.0	52.9	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2000	94.7	69.3	46.2	50.8	47.7	42.3	68.2	75.5	66.6	35.3	37.4	17.9	56.7	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2001	95.2	69.6	46.4	51.0	48.0	42.6	68.5	75.2	66.3	35.1	37.2	17.8	52.4	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2002	95.6	69.9	46.6	51.3	48.3	42.8	68.8	74.9	66.1	35.0	37.0	17.8	52.2	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2003	96.0	70.2	46.9	51.5	48.6	43.0	69.1	74.6	65.8	34.8	36.9	17.7	51.9	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2004	96.4	70.5	47.1	51.8	48.9	43.3	69.5	74.3	65.5	34.6	36.7	17.6	51.8	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2005	96.8	70.8	47.3	52.0	49.2	43.5	69.8	74.0	65.3	34.5	36.5	17.5	51.6	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2006	97.3	71.1	47.6	52.3	49.5	43.8	70.1	73.7	65.0	34.3	36.4	17.4	51.3	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2007	97.3	71.1	47.6	52.3	49.5	43.9	70.2	73.7	65.0	34.3	36.4	17.4	51.3	73.5	72.7	87.1	49.6	52.7	24.4	65.0	
2008	97.4	71.2	47.6	52.4	49.6	44.0	70.3	73.7	65.0	34.3	36.3	17.4	51.3	73.3	72.6	86.9	49.4	52.6	24.3	65.0	
2009	97.6	71.3	47.7	52.5	49.7	44.2	70.4	73.6	64.9	34.3	36.3	17.4	51.3	73.2	72.5	86.7	49.3	52.5	24.3	64.9	
2010	97.8	71.5	47.8	52.6	49.9	44.4	70.6	73.6	64.9	34.3	36.3	17.4	51.2	73.0	72.3	86.6	49.2	52.4	24.2	64.8	
2011	97.9	71.6	47.9	52.7	50.0	44.5	70.7	73.5	64.8	34.2	36.2	17.4	51.2	72.9	72.2	86.4	49.1	52.3	24.2	64.5	
2012	98.1	71.7	48.0	52.8	50.1	44.7	70.9	73.5	64.8	34.2	36.2	17.4	51.2	72.8	72.1	86.3	49.0	52.1	24.1	64.4	
2013	98.2	71.8	48.1	52.9	50.2	44.8	71.0	73.4	64.8	34.2	36.2	17.3	51.1	72.6	71.9	86.1	48.9	52.0	24.1	64.3	
2014	98.4	71.9	48.2	53.0	50.3	45.0	71.1	73.4	64.7	34.2	36.2	17.3	51.1	72.5	71.8	85.9	48.8	51.9	24.0	64.2	
2015	98.6	72.1	48.3	53.1	50.5	45.2	71.3	73.3	64.7	34.1	36.1	17.3	51.1	72.4	71.7	85.8	48.7	51.8	24.0	64.1	
2016	98.7	72.2	48.4	53.2	50.6	45.3	71.4	73.3	64.6	34.1	36.1	17.3	51.0	72.2	71.5	85.6	48.6	51.7	23.9	63.9	
2017	98.9	72.3	48.4	53.3	50.7	45.5	71.6	73.2	64.6	34.1	36.1	17.3	50.9	72.1	71.4	85.5	48.5	51.6	23.9	63.8	
2018	99.1	72.4	48.5	53.4	50.8	45.7	71.7	73.2	64.5	34.1	36.1	17.3	50.9	72.0	71.3	85.3	48.4	51.5	23.8	63.7	
2019	99.2	72.6	48.6	53.5	51.0	45.8	71.8	73.1	64.5	34.0	36.0	17.3	50.9	71.9	71.2	85.2	48.3	51.3	23.7	63.6	
2020	99.4	72.7	48.7	53.6	51.1	46.0	72.0	73.1	64.5	34.0	36.0	17.2	50.9	71.7	71.0	85.0	48.2	51.2	23.7	63.4	
2021	99.4	72.7	48.7	53.6	51.1	46.1	72.0	73.1	64.5	34.0	36.0	17.2	50.9	71.7	71.0	85.0	48.2	51.2	23.7	63.4	
2022	99.4	72.7	48.7	53.6	51.1	46.2	72.0	73.1	64.5	34.0	36.0	17.2	50.9	71.7	71.0	85.0	48.2	51.2	23.7	63.4	
Mean	96.8±2.2	70.8±1.6	47.3±1.2	52.0±1.3	49.2±1.6	43.8±1.6	69.8±1.8	74.3±1.4	65.6±1.2	34.7±0.7	36.7±0.8	17.6±0.4	51.9±1.3	72.9±0.7	72.2±0.6	86.4±0.8	49.1±0.5	52.2±0.6	24.2±0.3	64.5±0.6	
n	2	6	2		6	6		4	2	7		4		7	6	8	5		3		

4. Discussion

This study represents the first time that estimates of enteric methane emissions using the IPCC Tier 2 method were obtained at the national level in Zambia. The effort marks a significant improvement in the accuracy of Ent_{CH₄} emission estimates from Zambia's cattle sector for the period 1994 to 2022. This approach highlights the inherent relationships between cattle population

dynamics, production systems, and methane emissions, revealing significant implications for climate action and livestock management in Zambia.

The traditional beef production system had the largest cattle population and therefore made the largest contribution to the annual enteric methane emissions between 1994 and 2022, contributing 73% to 75% of annual total enteric methane emissions. The commercial dairy production system had the lowest cattle population. It therefore contributed the least to the annual enteric methane emissions, contributing 2.3% to 2.5% of the annual enteric methane emissions for the same period. While population-weighted average emission factors in the dairy production systems increased over the period studied, the IEF in the production system with the largest population decreased. The main driver of the increase in total cattle enteric methane emissions in Zambia from 1994-2022 was therefore the increasing cattle population, particularly in the traditional beef production system. This finding is in agreement with the report of Chang et al. (2021), suggesting that most of the increase in cattle GHG emissions in sub-Saharan Africa is because of increasing livestock populations. The high cattle population in the traditional beef production system is also linked to the fact that the smallholder farmers are averse to selling off their cattle for economic gains or profit due to the multifunctionality of cattle in socio-cultural settings, as pointed out by Odubote (2022) and Descheemaeker et al. (2016).

It is, however, important to mention that although there have been interventions to increase milk yield and feed digestibility over the period of study, the effects on average production parameters in each production system (mostly emergent dairy and beef production systems) and the small proportions of total cattle populations in these systems means that these changes have not had a significant impact on total cattle GHG emissions at national scale. This differs from some reports from South Africa (Caro et al., 2014; Tongwane & Moeletsi, 2020), Kenya (SDL, 2019) and Ethiopia (Wassie et al., 2022) showing that individual animal productivity (e.g. milk yield, LW, weight gain and calving rate) has significantly increased and emission intensity decreased in recent decades.

The present study showed notable variations in Ent_{CH_4} emission factor over the study period, driven by parameters such as growing cattle population growth, evolving production systems, and shifts in feed availability and quality. The traditional beef production system, which dominates Zambia's cattle production, is characterized by low productivity and reliance on poor-quality feed. These elements contribute to higher methane emission factors, as the low digestibility of feed increases the proportion of energy lost as methane during rumen fermentation. In contrast, commercial systems, though fewer in number, demonstrate the potential for reducing emissions intensity through improved management practices and better feed quality for higher productivity.

The total annual enteric methane emission reported in this study using the Tier 2 approach was found to be, generally, twice the methane emissions obtained using the Tier 1 approach as reported by Zambia Environmental Management Agency (ZEMA) (2020) in the first Biennial Update Reports (BUR). The average total annual methane emissions reported in the BUR for the period 1994-2016 using Tier 1 was $89.9 \text{ Gg CH}_4/\text{year}^{-1}$ (range 51.4 – 143.6). However, for this study, the average total annual methane emission obtained for the same period was $187.2 \text{ Gg CH}_4/\text{year}^{-1}$ (range 140.7 – 262.2). This is in agreement with the reports of Gurmu et al. (2024a and b) who compared the IPCC Tier 1 and Tier 2 methodologies in smallholder cattle systems in Ethiopia. Gurmu et al. (2024a) found that the IPCC Tier 2 methodology estimated a 39% higher gross energy intake and a 51% higher implied emission factor compared to a modified Tier 2 methodology based on the Commonwealth Scientific and Industrial Research Organization (CSIRO) approach. These discrepancies highlight the importance of selecting appropriate models tailored to local conditions. This variability underscores the importance of capturing system-specific data, as generalized continental emission factors used in the Tier 1 method fail to account for these dynamics (Graham et al. 2022). By integrating detailed data on feed characteristics, animal performance, and management practices, the Tier 2 method provided a more comprehensive understanding of Zambia's livestock emissions profile, enabling targeted mitigation strategies that are tailored to specific production systems.

The implied emission factor for dairy cattle increased over time partly because of the noted increase in milk yield in 2009 and subsequently again in 2017. The average implied emission factor obtained for dairy cattle commercial and emergent production systems (77.4 and 55.4 kg CH₄ head/year), respectively, are higher than the IPCC 2006 Tier 1 value of 46 kg CH₄ head/year for dairy cattle in Africa and the Middle East. In the same vein, the emission factors found for dairy cows in this study was higher (99.1 kg CH₄ head/year) than the IPCC (2019) default emission factor for dairy cows in low productivity systems (66 kg CH₄ head/year) and for dairy cows in high productivity systems (86 kg CH₄ head/year) in Africa. Du Toit et al. (2014) and SDL (2019) also reported higher Tier 2 emission factors for dairy cattle in South Africa (76 kg CH₄ head/year) and Kenya (70 kg CH₄ head/year), respectively, than the IPCC (2006) default emission factors for Africa.

The equations in the IPCC (2006) guidelines for determining the values of the emission factors is, by design, largely dependent on the values assumed for LW, feed energy digestibility, milk yield, and Y_m. The LW differs between breeds, sex and age, while feed energy digestibility is affected by feed characteristics, feeding (and grazing) practices, and feed basket quality. It is a fact that the LW, feed digestibility energy, and milk yield of dairy cows in Zambia and Ethiopia were higher than the values assumed for dairy cattle in Africa (IPCC, 2006). Hence, using IPCC (2006 and 2019) default values of emission factors for dairy cattle would underestimate enteric CH₄ emission when compared with emission factors developed using country specific information. These contrasting results highlight the need for developing country-specific emission factors that reflect the different cattle production systems and production performances in the different production systems.

Despite its advantages, the Tier 2 methodology relies on the availability of high-quality, country-specific data. In Zambia, data gaps on feed composition, seasonal variability in feed resources, and production parameters remain significant challenges. Addressing these gaps will require systematic data collection, research collaborations, and investments in livestock research infrastructure. Accurate and detailed GHG inventory data are essential for Zambia to meet its commitments under the Paris Agreement and its Nationally Determined Contributions (NDCs). The Tier 2 method enhances the credibility of Zambia's GHG inventories, providing a solid foundation for setting realistic mitigation targets. Future research should build on this work by integrating field-based measurements of feed characteristics and methane emissions, particularly under varying agroecological conditions. Scenario modeling could also explore the potential impacts of different mitigation strategies on emissions, productivity, and livelihoods. Engaging stakeholders across the livestock value chain, from smallholder farmers to policymakers, will be crucial for ensuring that research findings translate into actionable policies and programs.

One of the distinguishing requirements of the IPCC Tier 2 method is the high data requirement for disaggregated animal population and livestock activity data comprising production performances, feed characteristics and feed diet quality. Uncertainty analysis is a statistical tool that helps provide critical information for prioritizing methodological and data improvement plans (IPCC, 2019). Uncertainty analysis of the years 1994 and 2022 activity data for enteric fermentation emissions were estimated to be -15.9% and -19.7%, respectively. The uncertainty of emission factors compares well with the IPCC (2006) default uncertainty range for Tier 2 emission factors of $\pm 20\%$. The extensive beef system was found to be the most significant contributor to the uncertainty of enteric fermentation emissions. Factors responsible for the uncertainty in enteric include Y_m, C_f, feed digestibility, and live weight for cows, in addition to the population size. It must also be noted that this study used average values for activity data reported in a few years and different locations in the country, supplemented by expert judgement. These data sources may have affected the estimated uncertainty, which should be re-analyzed when better primary data is available. In particular, expert judgement was the main source of data for diet composition, which is a key input to the estimates of diet digestibility. Improvement in the data quality for these key activity data is critical to reducing the uncertainty of inventory estimates.

Uncertainty analysis in this study highlighted that investments in data improvement should be targeted to animal subcategory populations and key input parameters used to estimate the enteric

emission factors. The results of this analysis, therefore, support more cost-effective use of limited research resources by highlighting the systems, subcategories and parameters for which better data should be prioritized.

5. Conclusions

This study employed the IPCC Tier 2 method to estimate enteric fermentation emissions from cattle in Zambia. The cattle population and the enteric methane emissions are noted to have steadily increased from 1994 to 2022. The main driver of the increase in enteric methane emission is the beef cattle population under the extensive traditional production system, as there was no quantifiable data on improved cattle productivity. The dairy cattle population has largely remained at around 10% of the total cattle population. Since the dairy cattle production systems exhibited higher emission factors than the other cattle, it suggests that changes in the structure of the sector could affect the level and intensity of GHG emissions from cattle production in the future.

This study provides a foundation for improving GHG inventory accuracy in Zambia's livestock sector and highlights the need for targeted mitigation strategies. By transitioning to the Tier 2 method, Zambia can better align its climate action plans with its unique agricultural systems, ensuring that policies are both practical and equitable. This improved inventory is expected to strengthen Zambia's ability to measure, report and verify emissions and emission reductions from the livestock sector.

The use of country specific activity data to estimate enteric methane emissions using the IPCC Tier 2 method showed higher emissions than the IPCC default values for Africa. This gives further support to arguments for using country-specific livestock activity data to derive more accurate emission factors. The uncertainty analysis indicated that overall uncertainty could be reduced with more accurate livestock activity data for all the production systems. The ongoing national efforts to collect primary data on body weights, feed characteristics, and diet baskets are expected to improve the emission factors.

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Institutional Review Board Statement: Not applicable as this study was non interventional and did not involve animal subjects. The study utilized publicly available data such as cattle population data and historical archives of cattle performance records. All sources were accessed through open channels and were publicly accessible.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are contained within the article, supplementary material and as provided in the minimum dataset file. Further inquiries can be directed to the corresponding author.

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