Agriculture sector- Cattle Operations- Country-level Enteric Fermentation and Manure Management Emissions

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1. Introduction

According to the Food and Agriculture Organization (FAO) data (FAOSTAT), beef and dairy milk production systems are the largest contributors of greenhouse gas (GHG) emissions in the livestock sector, representing more than 60% of emissions in the sector and 14.5% of all anthropogenic sources (FAO 2013). Beef and dairy sector emissions are driven by two sources. The primary source is enteric fermentation emissions which consists of methane (CH_4) gas produced in the digestive systems of ruminants and to a lesser extent non-ruminants. The secondary source is GHG emissions from manure management, producing both methane (CH_4) and nitrous oxide (N_2O) emissions via aerobic and anaerobic decomposition of livestock manure, including the microbially-driven processes of nitrification and denitrification (Waldrip et al., 2016; Waldrip et al., 2020). These emissions occur within manure storage facilities common to beef and dairy cattle systems, as well as in-field where manure has been applied, or deposited by livestock (see the Supplemental Section for more information).

FAOSTAT is the primary global source of cattle information, which estimates emissions and stocks (populations total) at the country-level. The way FAOSTAT reports cattle subtypes and reporting latency creates challenges in identifying which cattle subtypes are managed in confinement systems, or operations, versus pasture systems as the emission sources and amounts vary across these types of operations. Additionally, the reported dairy and non-dairy cattle are presumed to be both in pasture and in some form of manure management system, creating a double counting issue. Without more accessible, publicly-available, and country specific reporting, FAOSTAT is the best option available to estimate cattle emissions globally.

Beginning March 2025, Climate TRACE identified the cattle subtypes that represent cattle in operations - dairies, ranch, farm, and feedlots - from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Services (NASS) data (Davitt, 2024). The detailed U.S. information replaced the FAOSTAT U.S. data. Furthermore, USDA data was used with U.S. individual cattle operations identified with the methodology, "*Agriculture sector- Enteric Fermentation and Manure Management Emissions from Cattle Operations*", to expand U.S. state coverage, to improve our understanding of U.S. state-level cattle inventories.

To generate emissions for years 2015–2024, Climate TRACE combined FAOSTAT and USDA cattle data, with individual cattle operations identified in each country, to estimate emissions from cattle in operations at the country-level globally. Furthermore, beginning November 2025, Climate TRACE is providing emission reduction solutions (ERS) to understand how changing certain practices and retrofitting equipment can reduce cattle emissions, with a focus on reducing enteric fermentation and manure management methane emissions. In order to perform ERS, this required our approach to estimate emissions to IPCC 2019 equations and emission factors (EFs) from "Chapter 10: Emissions from Livestock and Manure Management" and "Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application" were used to estimate emissions (IPCC 2019a; IPCC 2019b). A benefit of using IPCC 2019 is that it accounts for global shifts and changes in commercial cattle breeding and production practices which can impact enteric fermentation and manure management emissions derived for these sectors (IPCC 2019a).

2. Materials and Methods

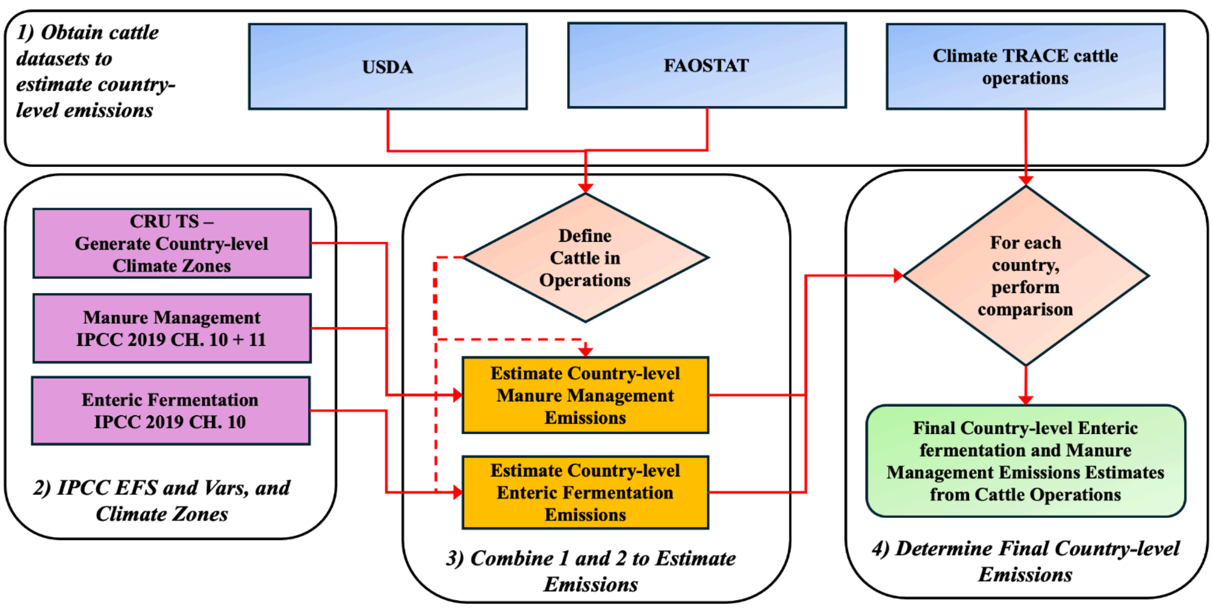

Figure 1 Flowchart depicting process to generate country-level enteric fermentation and manure management emissions from cattle operations. Box 1: FAOSTAT, USDA, and Climate TRACE cattle operations (asset) data were used to determine country-level cattle operations. Box 2: IPCC 2019 Chapters 10 and 11 EFs and equations were combined with cattle operations defined from USDA and FAOSTAT to estimate emissions. Box 3: Where Climate TRACE had identified individual cattle operations, a comparison was made between to determine which dataset to use to estimate final country-level emissions. Refer to the content below for more information on each box and dataset used. See the following section.

Figure 1 displays the overall process to estimate country-level enteric fermentation and manure management emissions from cattle operations. FAOSTAT and USDA datasets were employed to estimate country-level cattle operation emissions, defined as an operation that raises cattle in, but not limited to, animal feeding operations (AFOs), feedlots, ranches, farms, dairies, and cow-calf-operations (Rotz et al. 2019). Each dataset has different cattle definitions and processing steps in order to create a representative cattle in operations for county-level emissions. One the cattle subtypes that were in operations was identified, emissions were estimated using IPCC 2019 "Chapter 10: Emissions from Livestock and Manure Management" and "Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application were used to estimate emissions" (IPCC 2019a; IPCC 2019b).

2.1 Datasets employed

2.1.1 FAOSTAT

To estimate cattle in operations for all countries, except the U.S., FAOSTAT cattle stock items- "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" (beef and veal) and "Milk animals, Raw milk of cattle"- reported under the "Crops and livestock products" domain. Default regional EFs were applied to the data to estimate enteric fermentation and manure management emissions for years 2015 to 2023 (Figure 1).

FAOSTAT data for years 2015 to 2023 were accessed with the year 2024 forward-filled using 2023 data. This forward filling was done to match the USDA year range, which has data from 2015 to 2024. At the time of this study, the "Crops and livestock products" domain was selected since it provided the most recent updated cattle stock data, as of June 11, 2025 (accessed August, 2025). The domain "Emissions from Enteric fermentation and Emissions from Manure Management" was not used since it was updated February 12, 2025 and includes cattle stock data up to 2022. Additionally, the more recent version (February 27, 2025) provided updated "Flag" and "Flag Descriptions" where reported country-level data that has an "Estimated value" was updated to "Official figure". This provides some level of confidence in a country's reported data (see Table 5 for examples of these flags). Lastly, FAO livestock emissions data was not used since the estimates were generated using IPCC 2006 Equations and EFs.

For all countries, except the U.S., FAOSTAT items (cattle subtypes) were used from the domain "Crops and livestock products":

- "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" (beef and veal; *not equivalent* to "Cattle, non-dairy" above);
- "Milk animals, Raw milk of cattle".

Additionally, a country-level dataset was produced from the sector, "*Agriculture sector- Emissions from Enteric Fermentation and Manure Left on Pasture from Cattle*", that identified which countries have reporting discrepancies for beef cattle populations by comparing the stock type "Cattle, non-dairy" and "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled." This was used to filter out countries that were presumed to have no cattle operations exclusively devoted to beef, described further in section 2.2.2. Figure 1 provides an overview of the approach employed to estimate country-level emissions with FAOSTAT data.

2.1.2 USDA NASS

For the U.S., country-level estimates used a combination of U.S. Department of Agriculture (USDA) data and U.S.-identified cattle operations from "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*". USDA cattle subtypes were identified (see Figure 3 and discussed in section 2.2.2) and for each state by year, was compared to U.S.-identified cattle operations to determine which emission estimate to use, discussed in section 2.2.4.1. Figure 2 provides an overview of the process to estimate U.S. country-level emissions.

To estimate each U.S. states' cattle in operations for years 2015 to 2024, USDA NASS large dataset "qs.animals_products_20250607" was accessed (https://www.nass.usda.gov/datasets/; accessed June 9, 2025). For each state, the following "Categories" (cattle subtypes hereafter) were selected, after the "Data Item" was selected, to estimate U.S. country-level cattle operation emissions:

- CATTLE, COWS, MILK - INVENTORY;
- CATTLE, HEIFERS, GE 500 LBS, MILK REPLACEMENT - INVENTORY;
- CATTLE, ON FEED - INVENTORY

USDA data increased coverage at the state-level where Climate TRACE has no or partial coverage of cattle operations (see "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" methodology for more information). A breakdown and explanation for why these cattle subtypes were considered cattle in operations, and used to estimate emissions, is described in section 2.2.2. The approach to estimate emissions using USDA data is described in section 2.2.4.1.

2.1.3 Climate TRACE individual identified cattle operations

Individual cattle operations (assets) from the methodology "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" were incorporated into U.S. country-level emissions estimates. This novel methodology enables systematic identification of confined cattle operations across heterogeneous landscapes, addressing disparities in how such facilities are defined and reported. The cattle operations in this database, here defined as a location that raises cattle across in various confined ways, includes, but not limited to AFOs, feedlots, ranches, farms, dairies, and cow-calf-operations (Rotz et al. 2019). Each operation in a state was aggregated to the state-level to determine which data source, USDA or Climate

TRACE, offered the most coverage based on summed emissions. The approach to estimate emissions using Climate TRACE data is described in section 2.2.4.1.

2.1.4 IPCC 2019 Equations and EFs

Equations and EFs from The IPCC 2019 Chapter 10: Emissions from Livestock and Manure Management and Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application were applied to FAOSTAT and USDA to estimate emissions (IPCC 2019a; IPCC 2019b). Default IPCC "Other Cattle" and "Dairy Cows" EFs based on region, temperature, and manure management systems were applied to "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" and "Milk animals, Raw milk of cattle" populations, respectively.

Enteric fermentation emissions used section 10.3 and applied the Tier 1 approach to estimate dairy and other cattle CH_4 emissions. Manure management emissions used section 10.4 and 10.5 and EFs from Chapter 11, Table 11.3. A modification was made to make IPCC manure EFs and definitions usable for this effort: to determine the proportion of animals that were managed by a specific animal waste management system (AWMS), IPCC 2006 Tables 10A-4 and 10A-5 "Manure Region Management System Usage (MS%)" were used instead of the IPCC 2019 Table 10A.6. This was chosen since:

1) IPCC 2019 Table 10A.6 has more "sub-regional" information but not for all regions, which will make assigning central asian countries to an IPCC 2019 "sub-region" challenging. IPCC 2006 more generalized, coarser, regions that don't create this issue.
2) IPCC 2006 has manure management systems that are more reflective of what has been observed in {insert asset link}. For example, IPCC 2019 Table 10A.6 states East Asia and South-East Asia (Asia) has 1% average for liquid/slurry systems. However, asset-level identification research indicates this type of manure management system is more common which IPCC 2006 captures in Tables 10A-4 and 10A-5.

2.1.5 Climate Zones - Climatic Research Unit Gridded Time Series

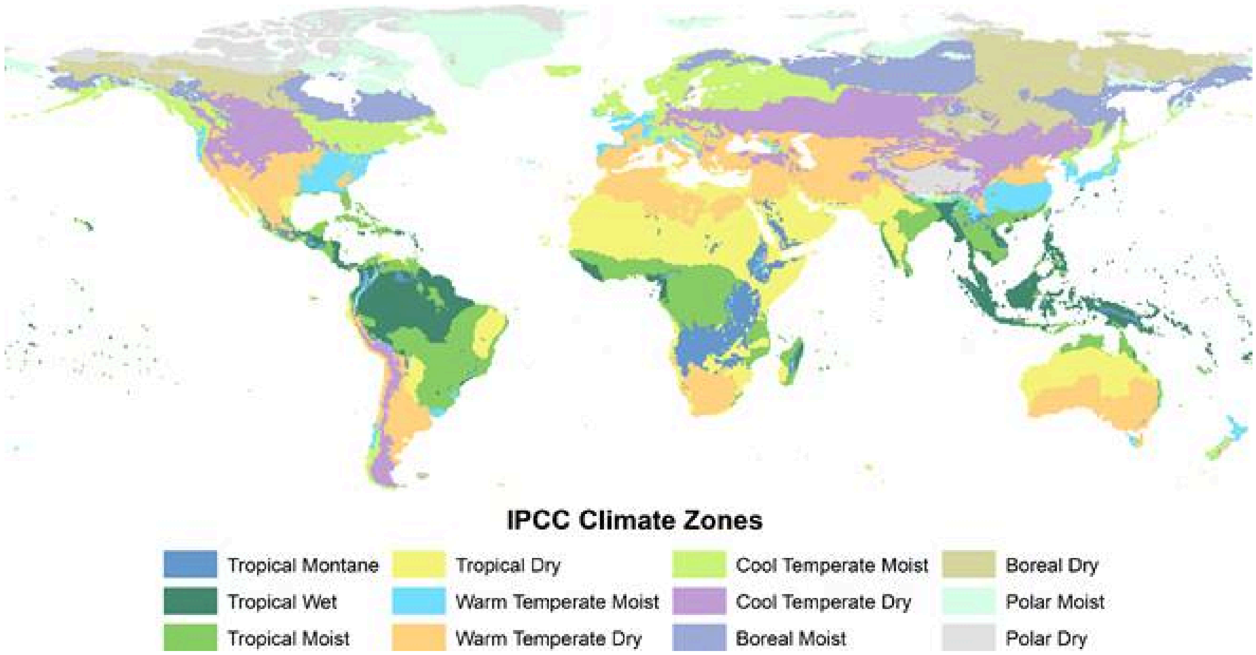

Figure 2 IPCC 2019 major climate zones identified (image taken from IPCC 2019 Chapter 3, volume 4; IPCC, 2019a).

The updated IPCC 2019 requires climate zones to estimate manure management methane emissions by manure management type, a change from IPCC 2006 which only used temperature-based EFs regardless of manure management type. To generate the climate zones for this sector, as shown in Figure 2, the Climatic Research Unit gridded Time Series (CRU TS) v4.09, released March 19, 2025, were taken from the Tropospheric Emission Monitoring Internet Service (TEMIS; https://crudata.uea.ac.uk/cru/data/hrg/; Harris et al., 2020). More detailed information on CRU TS can be found in the "*Reservoirs Emissions*" methodology in the Climate TRACE GitHub repository.

2.1.5 Emission Reduction Solutions (ERS)

Methane from enteric fermentation and manure management emissions is the primary focus for ERS. Both subsectors are approached separately with different strategies in order to achieve emission reductions.

A potentially effective emission reducing solution for enteric fermentation is introducing feed additives to dairy and beef diets. Feed additives are methane-inhibiting, meaning they discourage and reduce the bacteria that produce methane in the digestive system during the enteric fermentation process (see supplemental section S.2 for more information). For this ERS, studies have suggested that adding Agolin, Bovaer (also known as 3-NOP), or Monensin feed additives into cattle's diets can decrease emission factors by 10-45%, depending on the additive used and cattle type. The following references were compiled by additive type:

1. Agolin - Castro-Montoya et al. (2015) and Batley et al. (2024);
2. Bovaer - Hristov et al. (2015); Alemu et al. (2021); and Kebreab et al. (2023);
3. Monesin - Vugt et al. (2005); Odongo et al. (2007); Place et al. (2013); Tomkins et al. (2015); Vyas et al. (2018); and Cooke et al. (2024).

Each feed additive ERS strategy was applied to each cattle type at the country-level then averaged together to produce an overall mean ERS compared to the baseline emissions, the "business as usual", without ERS applied. We present this solution as a "best case scenario" since these feed additives may or may not be used in production in some cattle producing countries (IPCC 2019b). See Table S5 **"**Enteric Fermentation ERS strategies" in the "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" methodology for more information.

Effective emission reducing solutions for dairy and beef manure management systems is to modify and/or retrofit a current manure system to generate less methane emissions. This can involve shifting from an anaerobic to a more aerobic system (see supplemental section S.1 for more information) or changing practice - shifting from dry lot to dairy spread. For the manure management ERS, we used "Chapter 10: Emissions from Livestock and Manure Management" Table 10.14 as a look-up table to understand different scenarios when shifting from a default, higher, manure system to a lower methane emitting manure system. See Table S6 **"**Manure Management ERS strategies" in the "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" methodology for more information.

TABLE 10.14 (UPDATED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool				Temperate		Warm			
			Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Dairy Cattle	High Productivity	Uncovered anaerobic lagoon	96.5	[illegible]	[illegible]	[illegible]	117.4	122.2	122.2	128.6	128.6	128.6
		Liquid/Slurry, Pit storage > 1 month [5]	33.8	[illegible]	[illegible]	[illegible]	59.5	65.9	94.9	122.2	117.4	119.0
		Solid storage	3.2				6.4		[illegible]			
		Dry lot	1.6				2.4		[illegible]			
		Daily spread	0.2				0.8		1.6			
		Anaerobic Digestion -Biogas[8]	3.2				3.7		3.7			
		Burned for fuel	16.1									
	Low Productivity[1]	Uncovered anaerobic lagoon	52.3	58.4	43.6	42.7	63.6	66.2	66.2	69.7	69.7	69.7
		Liquid/Slurry, Pit storage > 1 month [5]	18.3	22.6	12.2	12.2	32.2	35.7	51.4	66.2	63.6	64.5
		Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			
		Daily spread	0.1				0.4		0.9			
		Anaerobic Digestion -Biogas[8]	9.2				9.5		9.5			
		Burned for fuel	8.7									

Country A - % of Cattle managed in this system

Country A - % of Cattle managed in this system

Figure 3 Table 10.14 from IPCC 2019 displaying the ERS for manure management. Red boxes indicate the current system and methane EF used in the climate zone for a country. Green dashed boxes in switching to a lower manure management EF within that same climate zone column.

For each manure management system within a country and climate zone, we assumed the "best case scenario" for what the emissions would be by shifting to the next lowest emitting manure management system in Table 10.14, shown in Figure 3. For example, if a Country A has uncovered anaerobic lagoons and solid storage (baseline), then a percentage of the dairy cattle population was assigned to each, based on IPCC 2006 Table 10A-4 and 10A-5. "Manure Region Management System (red boxes Figure 3). With the cattle population assigned to each manure management system, the EF was determined for each: 96.5 g CH_4 kg VS^{-1} and 6.4 g CH_4 kg VS^{-1} for uncovered anaerobic lagoons and solid storage respectively. To reduce manure emissions for these systems, the next lowest emitting system was selected. This shifts uncovered anaerobic lagoons to a liquid/slurry system and solid storage to dry lot (green dashed boxes in Figure 3). The shift to liquid/slurry system = 33.8 g CH_4 kg VS^{-1}, a 65% EF reduction, and to dry lot 2.5 g CH_4 kg VS^{-1}, a 62.5% EF reduction from baseline. Manure management methane emissions from high to lowest emitting systems were estimated based on the total number of cattle in each.

"Burned for fuel" was not included in this ERS approach since it falls under the sector "residential onsite fuel usage". Lastly, while shifting manure systems from anaerobic to aerobic can reduce methane emissions, the shift may slightly increase N_2O emissions. However, the CH_4 emissions from manure systems are significantly larger in amount relative to N_2O.

2.2. Methods

2.2.1 Defining cattle in an operation for a country

FAOSTAT and USDA NASS were used to determine the dairy and beef populations in operation for non-U.S. countries and U.S., respectively. In some cases FAO data identified countries with negative beef cattle populations, which were determined as "in-pature". The sections below describe each approach to determine cattle in operations for emissions estimates.

2.2.1.1 FAOSTAT

According to the FAOSTAT methodology, the cattle stock item "Producing Animals/Slaughtered" refers to "All data shown relate to total meat production, that is, from both commercial and farm slaughter." For cattle stock item "Milk animals" this is defined as "Data on cow milk production relate to total production of whole fresh milk" (FAOSTAT, 2023). As such, we treated the reported numbers for each item as representing cattle for beef production and for dairy production, respectively, in each country.

We opted not to use the "Cattle, dairy" and "Cattle, non-dairy" items since these data only provided population totals up to 2020. Additionally, the "Cattle, non-dairy" item does not represent cattle only meant for meat production and includes other cattle types. Table 2 highlights this where the USDA NASS cattle subtypes were totaled and matched the FAOSTAT "Cattle, non-dairy" population totals for years 2018 to 2021. The USDA NASS reported other cattle types - stockers, heifers, steers, and bulls - when providing numbers to FAOSTAT which reports these as "Cattle, non-dairy" (Table 2). These other cattle types are used as replacement for cattle on feedlots or to replenish the cattle population. The stockers, heifers, steers, and bulls can be considered foraging on pasture or grasslands to fatten up to the desired weight so they can be finished in feedlots (McKinley et al., 2004; Endres and Schwartzkopf-Genswein, 2018; Hayek and Garrett, 2018; Aubuchon, 2021). These other cattle types were not considered for emission estimates in this sector and were reported in Climate TRACE sectors "Emissions from Enteric Fermentation and Manure Left on Pasture from Cattle" since we consider these cattle types on pasture.

Table 2 USDA NASS cattle types mapped to FAOSTAT “Cattle, non-dairy” population for years 2018 to 2021. Note, data used in this table was from an FAOSTAT version March 24, 2023, and values may have changed since then.

Year	Data Item	Value	Year	Data Item	Value
2018	CATTLE, BULLS, GE 500 LBS - INVENTORY	2,252,300	***2020***	CATTLE, BULLS, GE 500 LBS - INVENTORY	2,237,400
	CATTLE, CALVES - INVENTORY	14,401,400		CATTLE, CALVES - INVENTORY	14,309,000
	CATTLE, COWS, BEEF - INVENTORY	31,466,200		CATTLE, COWS, BEEF - INVENTORY	31,338,700
	CATTLE, HEIFERS, GE 500 LBS - INVENTORY	20,217,800		CATTLE, HEIFERS, GE 500 LBS - INVENTORY	20,024,400
	CATTLE, STEERS, GE 500 LBS - INVENTORY	16,528,200		CATTLE, STEERS, GE 500 LBS - INVENTORY	16,541,200
	Total USDA NASS "non-dairy" =	***84,865,900***		***Total USDA NASS "non-dairy" =***	***84,450,700***
	FAOSTAT Cattle, non-dairy =	***84,865,900***		***FAOSTAT Cattle, non-dairy =***	***84,450,700***

Year	Data Item	Value	Year	Data Item	Value
2019	CATTLE, BULLS, GE 500 LBS - INVENTORY	2,253,000	***2021***	CATTLE, BULLS, GE 500 LBS - INVENTORY	2,210,500
	CATTLE, CALVES - INVENTORY	14,539,900		CATTLE, CALVES - INVENTORY	14,305,100
	CATTLE, COWS, BEEF - INVENTORY	31,690,700		CATTLE, COWS, BEEF - INVENTORY	30,843,600
	CATTLE, HEIFERS, GE 500 LBS - INVENTORY	20,210,000		CATTLE, HEIFERS, GE 500 LBS - INVENTORY	20,200,100
	CATTLE, STEERS, GE 500 LBS - INVENTORY	16,757,700		CATTLE, STEERS, GE 500 LBS - INVENTORY	16,787,800
	Total USDA NASS "non-dairy" =	***85,451,300***		***Total USDA NASS "non-dairy" =***	***84,347,100***
	FAOSTAT Cattle, non-dairy =	***85,451,300***		***FAOSTAT Cattle, non-dairy =***	***N/A***

To have a more representative cattle population for meat production, the same mapping exercise was applied to “Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled” (Table 3). By breaking down the USDA NASS data cattle types meant for slaughter, the “CATTLE, CALVES - SLAUGHTERED” and “CATTLE, GE 500 LBS - SLAUGHTERED” were identified as the cattle types for meat production and reported to FAOSTAT. Table 3 highlights this and shows the years 2018 and 2019 matching FAOSTAT “Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled”. Only two years, 2020 and 2021, had slightly different totals. This could be due to U.S. states revising initially reported county data after USDA NASS after it was submitted to FAOSTAT (U.S. National Agricultural Statistics Service, 2018).

Table 3 FAOSTAT "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" totals compared to USDA NASS slaughtered cattle population for years 2018 to 2021. When there is a positive difference between FAOSTAT and USDA NASS, FAOSTAT reported a higher volume of slaughtered beef cattle; negative numbers indicate USDA NASS reported a higher slaughtered beef cattle volume; and zero values indicate matching reported values between FAOSTAT and USDA NASS. Non-zero values in the difference row suggests a reporting entity updated their values since last submission. Note, data used in this table was from an FAOSTAT version March 24, 2023, and values may have changed in the most recent FAOSTAT update.

Year	Database	Element (FAOSTAT) or Data Item (USDA NASS) and Unit	Value
2018	FAOSTAT Crops and livestock products	Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled (An)	33,703,400
	USDA NASS	CATTLE, CALVES - SLAUGHTERED, MEASURED IN HEAD	603,600
	USDA NASS	CATTLE, GE 500 LBS - SLAUGHTERED, MEASURED IN HEAD	33,099,800
		Difference (FAOSTAT - USDA NASS) =	***0***
2019	FAOSTAT Crops and livestock products	Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled (An)	34,264,800
	USDA NASS	CATTLE, CALVES - SLAUGHTERED, MEASURED IN HEAD	608,900
	USDA NASS	CATTLE, GE 500 LBS - SLAUGHTERED, MEASURED IN HEAD	33,655,900
		Difference (FAOSTAT - USDA NASS) =	***0***
2020	FAOSTAT Crops and livestock products	Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled (An)	33,366,100
	USDA NASS	CATTLE, CALVES - SLAUGHTERED, MEASURED IN HEAD	479,800
	USDA NASS	CATTLE, GE 500 LBS - SLAUGHTERED, MEASURED IN HEAD	32,885,300
		Difference (FAOSTAT - USDA NASS) =	***1,000***
2021	FAOSTAT Crops and livestock products	Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled (An)	34,360,000
	USDA NASS	CATTLE, CALVES - SLAUGHTERED, MEASURED IN HEAD	413,500
	USDA NASS	CATTLE, GE 500 LBS - SLAUGHTERED, MEASURED IN HEAD	33,946,600
		Difference (FAOSTAT - USDA NASS) =	***-100***

Therefore, we assumed other countries with "Cattle, non-dairy" populations included other cattle types in this category and the "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" were more representative of cattle destined for meat production that came from some type of operation where the animals are confined for a certain amount of time to fatten them for slaughter. For FAOSTAT “Milk animals, Raw milk of cattle”, the reported values were treated as representing cows processed for milk production in some type of dairy farm operation.

2.2.1.2 USDA

USDA provided the cattle subtypes that were considered to be in an operation, as shown in Figure 3. USDA provided specific “Data Items”, or cattle subtypes hereafter, that were reported in the Cattle Inventory on their website (https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/). Not all cattle subtypes are in an operation and subtypes that are destined to be in an operation, specifically cattle that end up on feed, only have a percentage allocated. Described below is the identification process and cattle subtypes that were considered in an operation for each U.S. state (numbering based on Figure 4). For dairy operations, the subtypes considered in an operation (i.e., dairy farm):

1) CATTLE, HEIFERS, GE 500 LBS, MILK REPLACEMENT - INVENTORY
   - 100% of this subtype is assumed to be in a cattle operation of some type, i.e. dairy.
2) CATTLE, COWS, MILK - INVENTORY
   - 100% of this subtype is assumed to be in a cattle operation of some type, i.e. dairy.

For beef cattle (i.e. a farm, ranch, or a feedlot), USDA provided numerous cattle subtypes that are meant for the “Cattle for Beef System”. However, not all are in a feedlot on feed, only a percentage of them (Davitt, 2024). Figure 3, dashed lines, shows the beef cattle subtypes that are placed in and described below:

3) CATTLE, CALVES - INVENTORY
   - A percentage (unknown amount) is placed in the beef system.
4) CATTLE, HEIFERS, GE 500 LBS, (EXCL REPLACEMENT) - INVENTORY
   - 100% of the cattle in this subtype are considered to be placed in the beef system.
5) CATTLE, STEERS, GE 500 LBS - INVENTORY
   - 100% of the cattle in this subtype are considered to be placed in the beef system.

Subtypes 3, 4, and 5 are in the “Cattle for Beef System” as “On-Feed/Placement”, “Background”, and/or “Feeder Supply”, where a portion of these are then placed in a feedlot on feed:

6) CATTLE, HEIFERS & HEIFER CALVES, ON FEED - INVENTORY
   - Composed of subtypes 3 and 4.
7) CATTLE, STEERS & STEER CALVES, ON FEED - INVENTORY
   - Composed of subtypes 3 and 5.

The final beef cattle subtype considered in an operation was 8) CATTLE, ON FEED - INVENTORY CAPACITY: (1,000 OR MORE HEAD), which is made of subtypes 6 and 7. Note, “CATTLE, ON FEED - INVENTORY CAPACITY: (1,000 OR MORE HEAD)” only reports for feedlots representing ~85% of all fed U.S. cattle (as of 2024) and does not contain feedlots with a capacity of less than 1,000 head based on USDA Cattle on Feed survey (NASS, 2024). The subtype used here does not represent the actual total cattle on feed for each U.S. state but a large portion of the total.

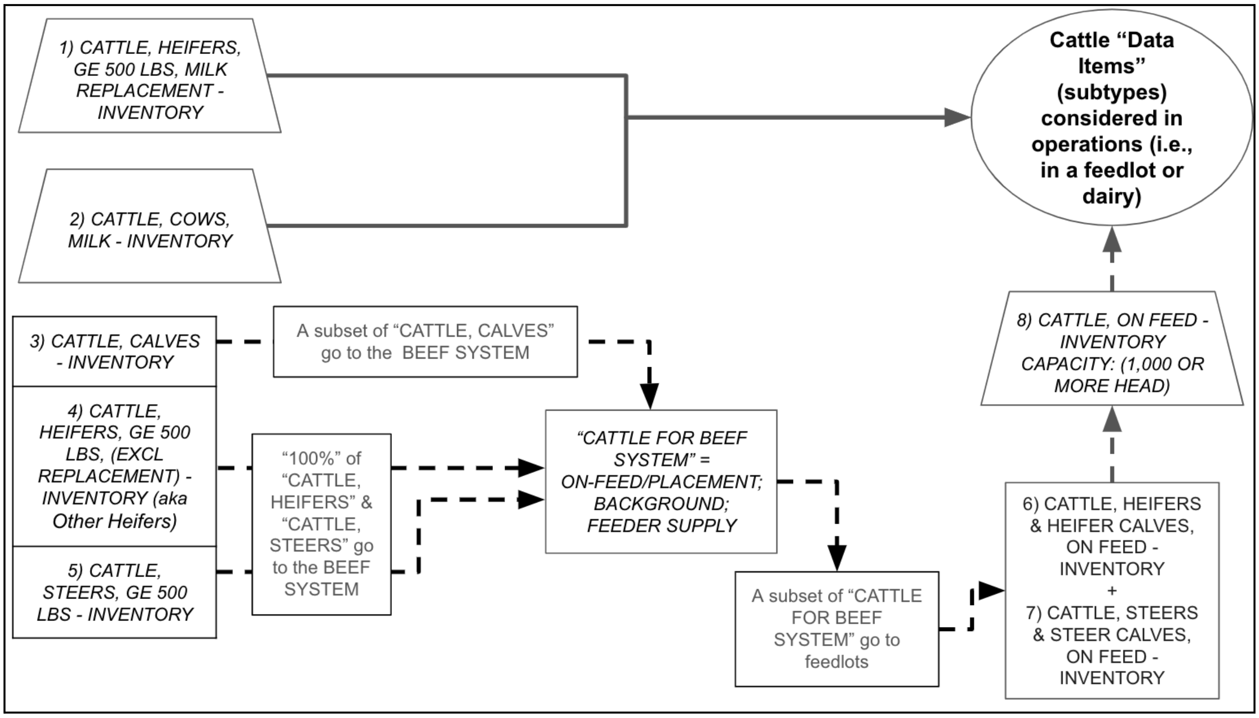

Figure 4 USDA NASS Data Items (cattle subtypes; parallelograms 1, 2, and 7) that were identified as the subtypes in cattle operations (circle). Included are the cattle subtypes - 3, 4, and 5 - that constitute the "Cattle for Beef System", which a portion are destined for "Cattle on Feed Inventory". Solid lines represent the cattle subtypes in the dairy system and dashed lines represent the cattle subtypes in the beef system.

Cattle subtypes 1, 2, and 8 were used in combination with individual cattle operations identified in "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" to estimate updated U.S. country-level emissions, discussed in section 2.2.4.1.

2.2.1.3 Countries with negative beef cattle populations

Some countries had their "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" populations set to zero for all years (Table S1). These data were interpreted as there were no feedlots for country-level emissions. This was due to FAOSTAT reporting "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" greater than the country's reported "Cattle, non-dairy" population. This may be due to FAOSTAT accounting for animals slaughtered in a separate country than where they are raised in the "Total meat production" category (FAOSTAT, 2023). Foreign imports can increase the slaughtered population to higher values relative to the "Cattle, non-dairy" population, which may not have been updated to reflect this change. See Table S1 for a list of countries with negative cattle values.

When "Producing Animals/Slaughtered" was greater than "Cattle, non-dairy" populations, a representative population for meat production could not be identified, as the remaining "Cattle, non-dairy" population would represent non-producing cattle - stockers, heifer, steers, and bulls - that are typically raised on pasture and accounted for elsewhere. (see section 2.1.1). Therefore, cattle beef operation emissions for these countries were not generated, only dairy emissions. Instead, these countries had their "Producing Animals/Slaughtered" populations reported in the Climate TRACE sector "*Emissions from Enteric Fermentation and Manure Left on Pasture from Cattle*" since they were considered to be foraging on pasture.

2.2.2 Assigning dairy and beef cattle to manure management types

Once the dairy and beef cattle in an operation for a country was determined, a portion of each population was assigned to their respective animal waste management system (AWMS). For this assigning, IPCC 2006 Tables 10A-4 and 10A-5 "Manure Region Management System Usage (MS%)" were used instead of the IPCC 2019 Table 10A.6 since IPCC 2019 Table 10A.6 has "no data" for certain AWMS whereas IPCC 2006 has values in Tables 10A-4 and 10A-5.

A modification was made to Table 10A-4 and 10A-5. "Manure Region Management System Usage (MS%)" for regions has "Other" column values with no explanation to what the "Other" column represents for AWMS in those regions. Therefore, the "Other" percentage was assigned to the most common, or the highest percentage, AWMS in that region. An example of this is shown in Table 5. As a result, the most dominant manure management system percentage is higher than what was reported in IPCC 2006 Table 10A-4 and 10A-5.

Table 5 An example of adjusting Table 10A-4 "Manure Management Methane Emission Factor Derivation for Dairy Cows" to include "Other" category type into the most common manure management system. Bold italicized values in the columns indicate what MS% were combined.

	Manure Management System (MMS) Usage (MS%)									**Adjusted MMS**
Region	*Lagoon*	*Liquid/ Slurry*	*Solid Storage*	*Drylot*	*Pasture/ Range/ Paddock*	*Daily Spread*	*Digester*	*Burned for Fuel*	*Other*	*Liquid/Slurry + Other*
North America	15.00	***27.00***	26.30	0.00	10.80	18.40	0.00	0.00	***2.60***	***27.00 + 2.60 = 29.60***
Region	*Lagoon*	*Liquid/ Slurry*	*Solid Storage*	*Drylot*	*Pasture/ Range/ Paddock*	*Daily Spread*	*Digester*	*Burned for Fuel*	*Other*	*Solid Storage + Other*
Western Europe	0.00	35.70	***36.80***	0.00	20.00	7.00	0.00	0.00	***0.50***	***36.80 + 0.50 = 37.30***

A proportion of the dairy and beef cattle in an operation were assigned to each manure management system in a country. For example, if there are 10,000 dairy cows in country A, and that country is in the North America region, then 2,960 dairy cattle are in an operation with a "liquid/slurry" system followed by 2,630 in a "solid storage" system. Any region that has cattle in "Pasture/Range/Paddock" were reported in the Climate TRACE sectors "*Emissions from Enteric Fermentation and Manure Left on Pasture from Cattle*". Cattle in the "Burned for Fuel" category were not included in the country-level emissions estimates and considered included in the Climate TRACE sector residential onsite fuel usage.

2.2.3 Deriving methane emission factors by climate zone per country

Manure management methane emissions are driven by 1) the amount of animal waste produced, 2) the manure system that handles the waste, and 3) the climate conditions, specifically temperature, that influences anaerobic and aerobic conditions (IPCC, 2019b; see supplemental section S.1 for more information on anaerobic and aerobic conditions). To reflect climate conditions' influence on manure management methane emissions, CRU TS data was used to generate country-level climate zones. However, for this work, a static climate zone spanning 30 years was not used to generate yearly emissions. Instead for each country, monthly climate zones were created then mapped to IPCC 2019 manure management systems EFs in Table 10.14 to obtain the correct grams of methane released per kilogram of volatile solid excreted. Table XX shows the climate zones and associated tables for mapping

For each identified country with a cattle operation, climate zones were generated based on the decision tree shown in the 1st Corrigenda ("things to be corrected") to the 2019 guidelines and discussed further in Chapter 10 (Figure2; Federici, 2021; IPCC, 2019b). The following CRU TS variables were used to generate the climate zones: temperature (TMP), frost day frequency (FRS), potential evapotranspiration (PET), and precipitation (PRE). The GMTED2010 global elevation data from Geffen (2023) was used with the CRU TS variables to define montane climate zones. Once the climates zones were derived monthly for years 2015 to 2024, the associated manure management methane EFs were taken from the IPCC 2019 Table 10.14 based on cattle type - Dairy Cattle or Non Dairy Cattle - then productivity type as defined for each region (IPCC, 2019b).

Table 6 IPCC 2019 climate zones mapped to manure management systems in Table 10.14 to derive CH_4 EFs and disaggregated climate zones mapped to N_2O EFs in Table 11.3. Note: Polar Dry and Moist, where it occurred, were mapped to Boreal Dry and Moist, respectively, since the majority of cattle occupy non-polar regions within a country.

<table>
<tr><th>IPCC Climate Zones for manure management systems (Table 10.14)</th><th>Disaggregated Climate Zones (Table 11.3)</th><th>IPCC Climate Zones for manure management systems (Table 10.14)</th><th>Disaggregated Climate Zones (Table 11.3)</th></tr>
<tr><td>Tropical Montane</td><td rowspan="5">Dry Climate</td><td>Tropical Wet</td><td rowspan="5">Wet Climate</td></tr>
<tr><td>Tropical Dry</td><td>Tropical Moist</td></tr>
<tr><td>Warm Temp. Dry</td><td>Warm Temp. Moist</td></tr>
<tr><td>Cool Temp. Dry</td><td>Cool Temp. Moist</td></tr>
<tr><td>Boreal Dry (Polar Dry)</td><td>Boreal Moist (Polar Moist)</td></tr>
</table>

The Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) was modified by Climate TRACE and country boundaries (level 0) were used to generate centroids to obtain the climate zones for each month in a given year. Countries with Arctic and subarctic regions (i.e., Canada, Alaska for U.S., and Russia) had their GDAM boundaries modified to minimize or remove arctic and subarctic regions when generating the centroids to extract the climate zones.

Once completed, Table 10.14 methane EFs by cattle type, productivity class, and manure management systems were identified for each country's climate zone to estimate methane emissions. The disaggregated climate zones were used to obtain Table 11.3 EF_4 [N volatilisation and re-deposition], kg N_2O–N (kg NH_3–N + NO_x–N volatilised)$^{-1}$ for wet or dry climate zones.

2.2.4 Emissions Estimates

All countries with cattle operations derived from FAOSTAT and USDA data estimated enteric fermentation methane emissions using IPCC 2019 "Chapter 10: Emissions from Livestock and Manure Management", section 10.3, applying the Tier 1 equation and "Other Cattle" and "Dairy Cows" Tier 1a EFs to estimate dairy and other (beef) cattle CH_4 emissions.

To estimate manure management methane and nitrous oxide emissions, the Tier 1 equations from IPCC 2019 "Chapter 10: Emissions from Livestock and Manure Management", sections 10.4 and 10.5, and EFs from Table 11.3 "Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application" were applied to FAOSTAT and USDA data to estimate emissions. Either the default or mean EFs for "Other Cattle" and "Dairy Cows" based on region, climate zone, and manure management systems were used in the Tier 1 equations.

Countries that have Climate TRACE asset-level, individual cattle operations identified, coverage from "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" went through another processing level to determine what emissions dataset to use, described below.

2.2.4.1 Comparison - USDA to Climate TRACE asset data for U.S. emissions

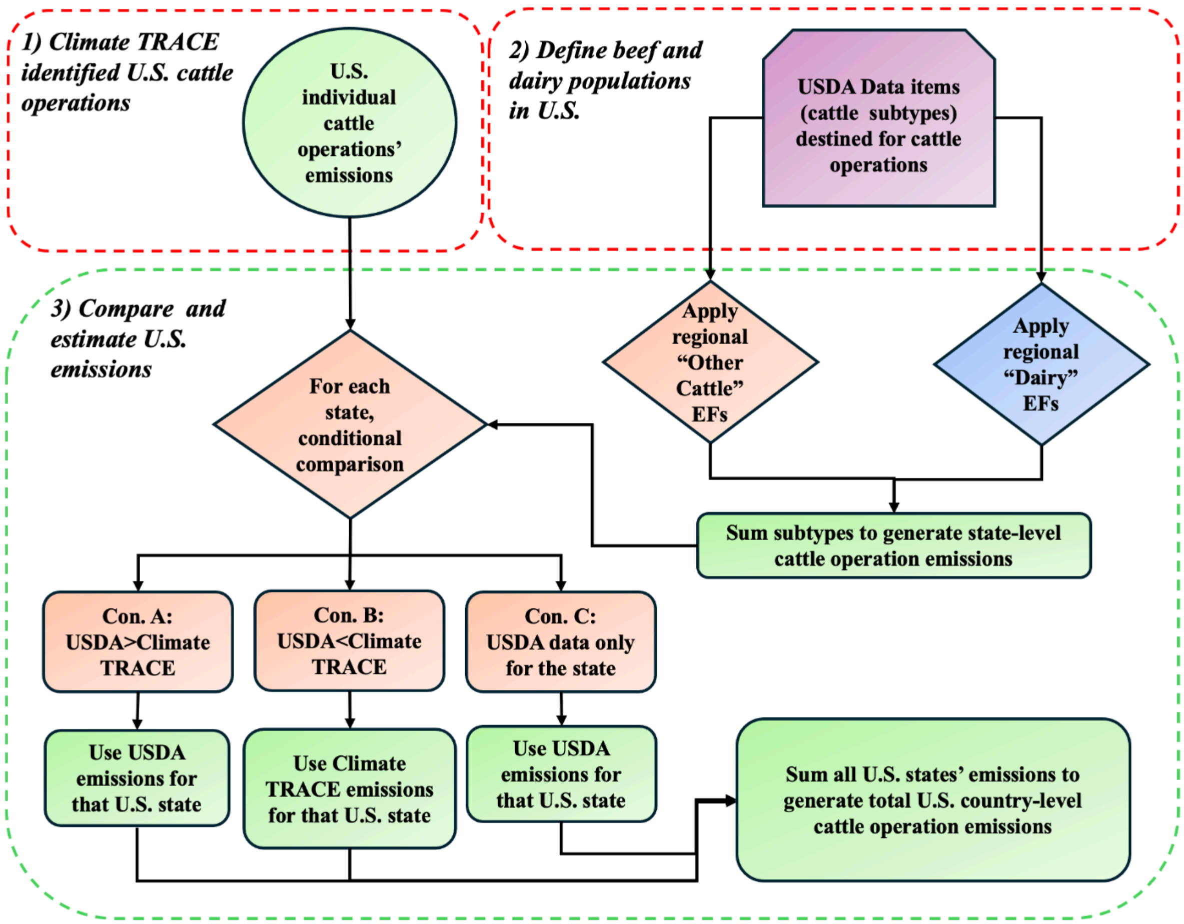

Figure 5 Flowchart describing the process to estimate U.S. country-level emissions combining USDA state data and Climate TRACE identified cattle operations. More information described in sections 2.2.2 and 2.2.4.1. Figure 3 details USDA cattle subtypes used to estimate emissions.

Each U.S. state with individual cattle operations identified had their emissions summed to the state-level, referred to as "Climate TRACE aggregated state cattle operations'". The aggregated emissions for each state was compared to USDA data to determine which emissions dataset to use for final state emissions data, shown in Figure 5 and based on the following conditions:

- *Condition A*: If USDA-estimated emissions > Climate TRACE aggregated cattle operations' emissions for that state, then USDA emission values replaced Climate TRACE emission values for that state by year;

- *Condition B*: If USDA-estimated emissions <= Climate TRACE aggregated cattle operations' emissions for that state, then Climate TRACE aggregated cattle operations' emissions were used for that state and year;
- *Condition C*: Where Climate TRACE had no asset coverage in that state, then USDA data was automatically assigned.

Once each condition was applied to each state per year, state-level estimate enteric fermentation CH_4, and manure management CH_4 and N_2O emissions were summed to produce a final U.S. country-level emissions totals. As a result, USDA increased the emissions coverage at the state-level where Climate TRACE was unable to identify individual cattle operations for the 2024 release and CLimate TRACE asset data increased coverage where USDA data may underreport cattle in operations.

2.2.4.2 Comparison - FAOSTAT to Climate TRACE asset data for Non-U.S. emissions

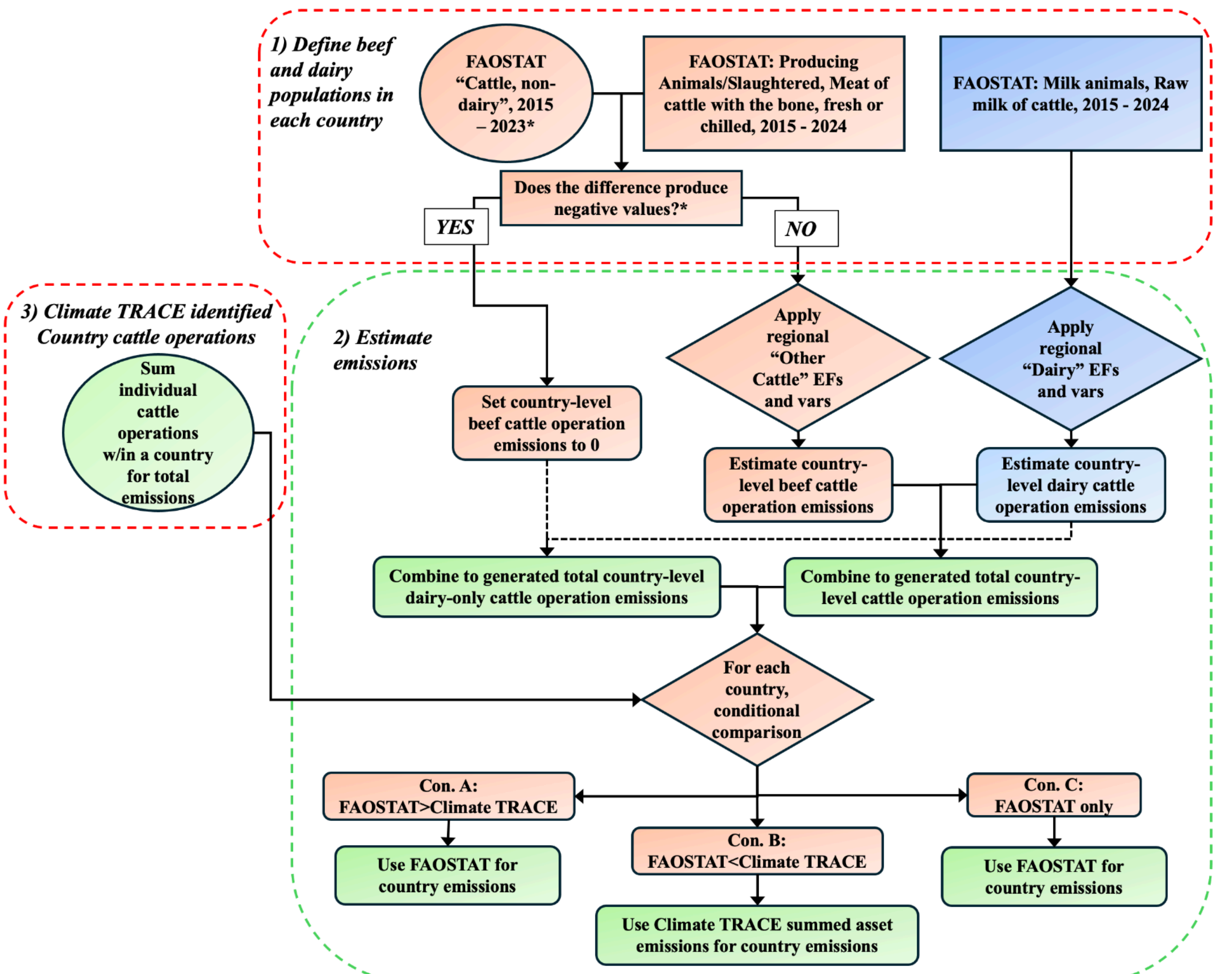

Figure 6 Flowchart describing the process to estimate non-U.S. country-level emissions by comparing FAOSTAT data to Climate TRACE identified cattle operations. More information

described in text below. An asterisk in certain shapes indicates this step was performed for the "*Cattle Emissions from Enteric Fermentation and Manure Left on Pasture*" and incorporated into this sector to estimate country-level confined emissions.

Each country with individual cattle operations identified had their emissions summed to the country-level, which we refer to as "Climate TRACE aggregated country cattle operations' emissions". These aggregated assets within a country were compared to FAOSTAT country data to determine which dataset to use, shown in Figure 6 and based on the following conditions:

- *Condition A*: If FAOSAT-estimated emissions > Climate TRACE country aggregated cattle operations' emissions for that country, then FAOSTAT emission values were used for that country;
- *Condition B*: If FAOSAT-estimated emissions <= Climate TRACE aggregated country cattle operations' emissions for that country, then Climate TRACE aggregated country cattle operations' emission values were used for that country;
- *Condition C*: If only FAOSAT-estimates and no Climate TRACE assets exist for that country, use FAOSTAT derived emissions.

Applying this conditional framework globally revealed substantial variation in the country definition of what cattle types are in cattle operations. Applying this approach improved the representativeness of aggregated Climate TRACE emissions and highlighting where country inventories may under- or over-represent the cattle type on confined systems.

2.2.5 Final Country-level Emissions

Country-level enteric fermentation CH_4 and manure management CH_4 and N_2O emissions estimates were generated and reported as separate sub-sectors on the Climate TRACE website (https://climatetrace.org/). To generate CO_2 equivalent (CO_2e) for 20 year and 100 year global warming potentials (GWPs), 79.7 (20 year) and 27.0 (100 year) Methane - non fossil values were applied to total country-level CH_4 emissions for each year. For total country-level N_2O emissions, a 273 value was applied for each 20 and 100 year GWPs. The manure management sub-sector summed each CH_4 and N_2O emissions into 20 and 100 year GWPs emissions values. More information on specific data fields and values are described in the Supplementary section.

Of the 250 countries and administrative regions reported for this sector, 156 had emissions estimated generated for years 2015 to 2023. The remaining 94 countries and administrative regions (i.e., Bermuda, Palau, and Tuvalu) either do not report or have cattle information in FAOSTAT, or we assumed to have cattle on pasture based on section "2.2.1.3 Countries with negative beef cattle populations" and their emissions estimates were set to zero for all years.

2.2.5.1 Final Country-level ERS Emissions

To understand the ERS applied, and the methane emissions reduced, each subsector enteric fermentation and manure management, *s*, has a*"ch4_emissions_factor_new_to_old_ratio"* designated that defines the relative emissions reduced:

$$ch4\_emissions\_factor\_new\_to\_old\_ratio_{s,c,y,t} = \frac{\sum CH_4 Emissions\ Reduced_{s,c,y,t}}{\sum CH_4 Emissions\ Default_{s,c,y,t}}$$

The ratio is the summation of *CH_4 Emissions Reduced* and *CH_4 Emissions Default* for each subsector, *s*, per country, *c*, year, *y*, and cattle type, *t*.

Applying the feed additives ERS to estimate *CH_4 Emissions Reduced* required estimating the mean feed additive, *f*, percent reduction for all additives applied to each dairy or beef cattle. For the manure management ERS, described in section 2.1.5, *CH_4 Emissions Reduced* was estimated by using a lower emitting manure management system EF then determining the total emissions for each dairy or beef cattle in that lower emitting manure management system. Once *CH_4 Emissions Reduced* was estimated, this was compared to the *CH_4 Emissions Default*, the default, higher emitting, manure system used for each dairy or beef cattle. Tables SM1 and Table SM2 provide examples for each sub-sectors ERS.

3. Discussion and conclusion

By developing a more representative cattle inventory for dairy and beef production using FAOSTAT and USDA NASS cattle data, Climate TRACE produced country-level datasets that more accurately identify the cattle types in operations and their resulting emissions. The inclusion of USDA NASS cattle data provided improved coverage and representation of cattle in operations within the U.S. Additionally, the mapping exercise performed in section 2.2.1 identified that FAOSTAT and USDA NASS datasets are periodically updated with new releases, which can create discrepancies in reported emissions over time.

Future work includes improving 1) the representation of cattle in operations and folding them into country-level estimates, 2) emission factors (EFs), 4) climate zones, and 3) assigning manure management types at the country-level. For 1) further explore why countries that produced negative differences (section 2.2.1.3) have these values generated. This can include import/export data to help identify domestically bred and slaughtered cattle. 2) Country-specific EFs, beyond IPCC 2019 regional EFs, will be researched to reflect changes in cattle practices in meat and dairy production in different countries. 3) To refine climate zones used for manure management emissions, countries that have spatially distributed cattle density information can be used to obtain climate zones more reflective of where cattle live instead of taking a whole country average. For example, in Australia, the cattle density is concentrated near the coasts and less so within the interior; in Russia, cattle management is focused in relatively temperate regions in the south and west, whereas country wide average temperatures are heavily influenced by large land areas in the north and east with colder climates. 4) IPCC manure management types are regional, not country-level. As a result, certain countries can have too much of a manure management system assigned to cattle, which overestimates manure management emissions. For example, Afghanistan agriculture and cattle practices rely on traditional farming and pastoral systems (UNEP, 2017; U.S. Department of State, 2017). This indicates the country has limited infrastructure for cattle operations. As a result of this work, Afghanistan dairy cattle are assigned to a lagoon and liquid/slurry systems, which isn't necessarily reflective of the cattle practices employed in the country. Other countries will be researched to determine if this over assignment of manure management systems occurs.

When folding in data from the "*Cattle Operations- Asset-level Enteric Fermentation and Manure Management Emissions*" methodology, substantial variation in both the spatial distribution and facility design of cattle operations was identified. These differences were pronounced in countries reporting the largest cattle populations (identified by FAOSTAT), with consistency diminishing as analyses were extended to countries with comparatively smaller cattle populations. For example, in the U.S., large-scale facilities formally designated as Concentrated Animal Feeding Operations (CAFOs) exhibit highly standardized layouts. By contrast, India's livestock sector comprises a complex mix of industrial dairies and informal gaushalas (cow shelters) that house large cattle populations but lack centralized monitoring. In Pakistan, urban cattle colonies located within dense city clusters represent a unique footprint type that diverges from conventional feedlot or dairy definitions. Meanwhile, in Brazil, semi-intensive and pasture-based systems, particularly in the Amazonia region, often combine confined feeding areas with open grazing, creating mixed operations. Overall, these variations emphasize the importance of region-specific representation in global emission estimates and demonstrate how integrating multi-source detection approaches improves comparability across countries.

These collective efforts strengthen Climate TRACE's capability to produce consistent, transparent, and spatially detailed estimates of livestock-related GHG emissions, supporting continual improvement in global emissions monitoring and reporting.

4. Supplementary Metadata Section

The Agriculture sector: *Country-level Enteric fermentation and Manure Management Emissions Estimates from Cattle Operations* sector reports the following data on the Climate TRACE website:

- Country-level enteric fermentation CH_4, and 20 and 100 year GWPs emissions from cattle operations
- Country-level manure management CH_4 and N_2O emissions, and 20 and 100 year GWPs from cattle operations

Emissions estimates were reported for years 2015 to 2024. The country-level cattle emissions described here encompasses the asset-level emissions estimates from the Climate TRACE agriculture sector: "*Agriculture sector- Enteric Fermentation and Manure Management Emissions from Cattle Operations*", meaning the aggregated cattle operations' emissions represent a subset of emissions contained in country-level emissions estimates. This sector does not include cattle on pasture emissions. All data is freely available on the Climate TRACE website (https://climatetrace.org/). A detailed description of what is available is described in Table S2.

Table SM1 Metadata for Country-level Enteric fermentation and Manure Management Emissions Estimates from Cattle Feedlots and Dairies**.**

General Description	Definition
Sector definition	*Country-level cattle operation emissions*
UNFCCC sector equivalent	*3.A.1 Cattle*
Temporal Coverage	*2015 – 2024. Non U.S. countries 2024 data was forward filled with FAOSTAT 2023 data. Emissions for 2025 forward filled post-processing*
Temporal Resolution	*Annual (original); Monthly (on website, see Temporal Disaggregation of Emissions Data for the Climate TRACE Inventory)*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of countries available for download	*250 countries*
Total emissions for 2024	*Total Enteric Fermentation CH_4 emissions = 421,346,300 metric tons* *Total Manure Management CH_4 emissions = 58,090,300 metric tons* *Total Manure Management N_2O emissions = 941,426.40 metric tons*
Ownership	*Country*
What emission factors were used?	*IPCC 2019 CH. 10 and 11 EFs*
What is the difference between a "0" versus "NULL/none/nan" data field?	*"0" values are for true non-existent emissions. If we know that the sector has emissions for that specific gas, but the gas was not modeled, this is represented by "NULL/none/nan"*
total_CO2e_100yrGWP and total_CO2e_20yrGWP conversions	*Climate TRACE uses IPCC AR6 CO_2e GWPs. CO_2e conversion guidelines are here: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf*

Table SM2 An ERS example for enteric fermentation emissions. The "ch4_emissions_factor_new_to_old_ratio" column is described in section 2.2.5.1; The "strategy_id" column is the feed additives alpha numeric ids applied at the country-level to reduce dairy and beef enteric fermentation emissions; the "strategy_name" column describes the name of the feed additives applied at the country-level. Note- each strategy identifier is specific to a feed additive used for beef or dairy cattle.

iso3_country	**year**	**ch4_emissions_factor_new_to_old_ratio**	**native_strategy_ids**	**strategy_name**
USA	2015	0.788	1a;1b;1c;2a;2b;2c	include agolin, bovaer, and monesin feed additive to the beef or other cattle and dairy cattle diet

Table SM3 An ERS example for manure management emissions. The "ch4_emissions_factor_new_to_old_ratio" column is described in section 2.2.5.1; The "mms_type" column describes the default manure management system (mms) used in the country with the"strategy_id" column providing their corresponding alpha numeric ids; the "strategy_mms" column displays the lower emitting mms to employ for ERS at the country-level with the "strategy_id_ers" column providing their corresponding alpha numeric ids. Note: each strategy identifier is specific to a mms used for beef or dairy cattle.

iso3_country	**year**	**ch4_emissions_factor_new_to_old_ratio**	**mms_type**	**native_strategy_ids**	**strategy_mms**	**strategy_id_ers**
USA	2015	0.328	DailySpread; Drylot; Lagoon; Liquid/Slurry; SolidStorage	1a;2a; 2c;3a; 4c;5a	DailySpread; Drylot; Liquid/Slurry; SolidStorage	2a;3a; 3c;4a; 5a;5c

Citation format: Davitt, A., Tulloch, A., Thomas, P., Piscopo, A., and Schiller, S. (2025). *Agriculture sector- Country-level Enteric fermentation and Manure Management Emissions Estimates from Cattle Operations.* WattTime and Carbon Yield, USA, Climate TRACE Emissions Inventory. https://climatetrace.org [Accessed date]

Geographic boundaries and names (iso3_country data attribute): The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on Climate TRACE are generated from the Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) along with their corresponding ISO3 codes, and with the following adaptations:

- HKG (China, Hong Kong Special Administrative Region) and MAC (China, Macao Special Administrative Region) are reported at GADM level 0 (country/national);
- Kosovo has been assigned the ISO3 code 'XKX';

- XCA (Caspian Sea) has been removed from GADM level 0 and the area assigned to countries based on the extent of their territorial waters;
- XAD (Akrotiri and Dhekelia), XCL (Clipperton Island), XPI (Paracel Islands) and XSP (Spratly Islands) are not included in the Climate TRACE dataset;
- ZNC name changed to ‘Turkish Republic of Northern Cyprus’ at GADM level 0;
- The borders between India, Pakistan and China have been assigned to these countries based on GADM codes Z01 to Z09.

The above usage is not warranted to be error free and does not imply the expression of any opinion whatsoever on the part of Climate TRACE Coalition and its partners concerning the legal status of any country, area or territory or of its authorities, or concerning the delimitation of its borders.

Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

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6. Supplemental Section

Table S1 Cattle population 2023 data in countries where the "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" populations are larger than "Cattle, non-dairy" population. Negative values indicate years where all "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" were interpreted to mean that no beef operations generated emissions at the country-level.

Country	ISO3	Cattle, non-dairy	Producing Animals/Slaughtered	Difference
Albania	ALB	20,984	245,097	-224,113
Armenia	ARM	279,797	496,293	-216,496
Azerbaijan	AZE	1,110,798	1,366,481	-255,683

Bahamas	BHS	79	110	-31
Bahrain	BHR	2,317	6,520	-4,203
Brunei Darussalam	BRN	238	3,367	-3,129
Israel	ISR	464,177	484,449	-20,272
Jordan	JOR	33,478	132,161	-98,683
Lebanon	LBN	25,991	212,562	-186,571
Mauritius	MUS	360	7,425	-7,065
Morocco	MAR	1,303,681	1,400,000	-96,319
Palestine	PSE	18,086	66,071	-47,985
Sao Tome and Principe	STP	1,039	1,757	-718
Syrian Arab Republic	SYR	370,407	409,006	-38,599
Tunisia	TUN	168,600	221,826	-53,226
United Arab Emirates	ARE	65,367	80,637	-15,270

S.1 Greenhouse Gas Emissions from manure management: Uncovered anaerobic lagoons & liquid/slurry systems

On large dairy and beef farms, animals produce huge amounts of manure every day. To manage this waste, farmers often rely on uncovered anaerobic lagoons and slurry pits. Uncovered anaerobic lagoons and liquid slurry systems are two of the most common ways to store manure. Farmers also rely on them because they are relatively cheap and can hold large volumes of waste. Lagoons and slurry pits also help settle solids and reduce odors, so they require less day-to-day maintenance compared with more advanced treatment systems such as covered lagoons with gas capture, anaerobic digesters that turn manure into biogas, or composting facilities that actively aerate and treat the waste. (IPCC, 2019b).

S.1.1 Lagoons Systems

But this convenience comes with an environmental cost. Lagoon systems create conditions where oxygen is scarce, which shifts manure decomposition away from normal aerobic breakdown (with oxygen) toward anaerobic digestion (without oxygen). In this process, specialized microbes called methanogens take over. Methanogens are a group of *Archaea* that live only in oxygen-free environments. Instead of using oxygen for energy, they break down simple carbon compounds in the manure — such as hydrogen and acetate produced by other microbes — and release methane (CH_4) as their waste product (Owen & Silver, 2014). In uncovered lagoons, the stagnant, oxygen-poor conditions are a perfect environment for these microbes, and the methane they produce escapes freely into the atmosphere. Some carbon dioxide (CO_2) is also produced at the surface where oxygen is present, though methane dominates under anaerobic conditions (Grant et al., 2015). Although much less than methane, small amounts of nitrous oxide (N_2O) can form near the lagoon surface. This is where the oxygen and nitrogen compounds can interact, or later when lagoon effluent is spread onto fields (Ding et al., 2016). Because N_2O has a global warming potential about 265-298 times greater than CO_2 over a 100-year timescale, and remains in the atmosphere for more than a century, even small releases are environmentally significant (IPCC, 2019b; IPCC, 2019c). Methane emissions are especially high in warm climates because higher temperatures accelerate microbial metabolism, allowing methanogens to grow faster and convert more organic matter (known as volatile solids) into methane (Grant et al., 2015).

S.1.2 Slurry Systems

In liquid slurry systems, manure is stored as a thick liquid in pits or tanks, because the manure is waterlogged (oxygen cannot penetrate deeply) leaving most of the storage anaerobic. As in lagoons, methanogens thrive in these oxygen-free zones and steadily produce methane (Owen & Silver, 2014). The top layer may have some oxygen when exposed to air, but deeper layers remain sealed off for months at a time. When the slurry is stirred, pumped, or spread onto fields, the trapped methane and carbon dioxide can be released in sudden bursts (Leytem et al., 2011). Furthermore, some nitrous oxide (N_2O) is also formed when nitrogen in the slurry briefly encounters oxygen, making this system a source of multiple greenhouse gases (IPCC, 2019, Chapter 10).

Together, lagoons and slurry systems are among the largest sources of greenhouse gases from livestock farming. They continuously generate methane and carbon dioxide, and under certain conditions they also emit nitrous oxide (Grant et al., 2015; Leytem et al., 2011). Due to the wide use of these systems, even small improvements in how they are managed could have a big impact on agricultural emissions. Strategies such as covering lagoons to capture biogas, installing anaerobic digesters, or improving manure handling before storage are being explored as ways to reduce this climate footprint (IPCC, 2019, Chapter 10).

S.2 Ruminant Digestion: A Specialized System for Tough Plant Matter

Cattle and other ruminants, such as goats and sheep, have evolved a four-chambered stomach that allows them to digest grasses and fibrous plants that most animals cannot (Foster, 2024; University of Minnesota Extension, 2025; Figure S1.). This adaptation gave them access to a food supply — cellulose-rich plants — that would otherwise be unavailable, helping them thrive in grassland ecosystems where few alternatives exist (FAO, n.d.). Ruminant digestion is a remarkable evolutionary solution that lets cattle and other animals survive on fibrous plants. At the same time, the methane released during this process has become a central issue in climate change discussions. Understanding how ruminant digestion works—and why it leads to methane emissions—is critical for developing strategies to feed the world while reducing agriculture's environmental footprint.

Grasses and fibrous plants first enter the rumen, which is a large fermentation chamber where billions of microbes begin breaking down plant fibers (University of Minnesota Extension, 2025). The reticulum works closely with the rumen, helping trap foreign objects and mixing food so it can be regurgitated and re-chewed as cud. Afterward, the omasum absorbs water and minerals, while the abomasum — often called the “true stomach” — digests food with acids and enzymes in a way similar to the human stomach (Foster, 2024).

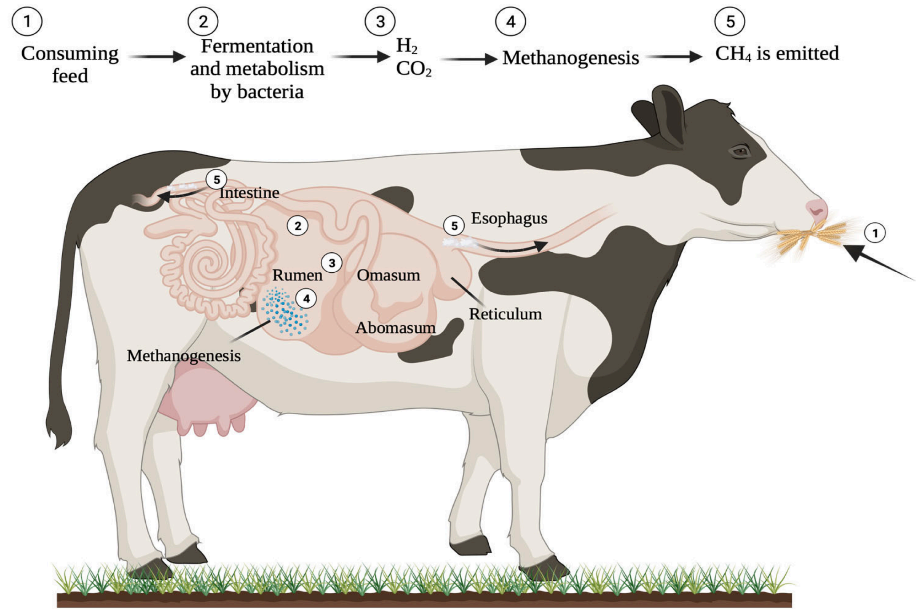

Figure S1. Cattle inner stomach chambers along with microbial processes associated with methane generation from within the cattle. Reproduced from Džermeikaitė, K., Krištolaitytė, J. & Antanaitis, R. (2024).

Humans lack cellulase, the enzyme needed to break down cellulose, which is a tough carbohydrate that makes up plant cell walls (Basile et al., 2023). As a result, raw grass passes through our digestive system without providing energy. Cattle however, rely on a symbiotic microbial community in their rumen. These microbes produce the necessary enzymes to break cellulose down into nutrients that the cow can absorb as energy and protein (Garnsworthy et al., 2019; University of Minnesota Extension, 2025).

This microbial process makes ruminant digestion possible, but it also produces a significant by-product: methane released mainly through belching (Garnsworthy et al., 2019). Inside the rumen, microbes digest food through anaerobic fermentation (a process without oxygen) which releases :

- Volatile fatty acids (VFAs) – the cow’s main source of energy (Bergman, 1990);
- Microbial protein – later digested by the animal;
- Heat;
- Gases - primarily carbon dioxide (CO_2) and methane (CH_4).