Agriculture sector- Country-level Enteric fermentation and Manure Management Emissions Estimates from Cattle Operations

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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.

FAOSTAT is the current source for global cattle information, which provides emissions and stocks (populations total) at the country-level under the domains "Emissions from Enteric fermentation and Emissions from Manure Management" and "Crops and livestock products", respectively (https://www.fao.org/). Each domain has the following:

1. In the FAOSTAT domain "Emissions from Enteric fermentation and manure management", emissions are broken down by item or by the cattle type:
    a. "Cattle, dairy";
    b. "Cattle, non-dairy".

"Cattle, dairy" and "Cattle, non-dairy" types include the total number of animals of the genus *Bos* used for milk or meat production for human consumption, respectively.

2. In the domain "Crops and livestock products" cattle types with each providing a total number of animals are:
    a. "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" (beef and veal; *not equivalent* to "Cattle, non-dairy" above);
    b. "Milk animals, Raw milk of cattle" (*equivalent* to "Cattle, dairy" above).

Each domain differs in recency of years reported and with "Crops and livestock products" has more up-to-date information that can lead to differences in reported total number of animals. Because of different version updates and years reported, there is a lack of consistency across FAOSTAT reporting domains, described further in section 2.1.1.

How FAOSTAT reports cattle populations and differences in reporting recency creates challenges in identifying which cattle types are managed in confinement systems versus pasture systems as the emission sources and amounts vary across these types of operations. The Climate TRACE coalition seeks to provide the most up-to-date information on country-level cattle operations emissions globally. Livestock production and processing data tend to be reported and available from FAOSTAT sooner than FAOSTAT's emissions data. In order to produce more timely emissions data, Climate TRACE developed an approach using the most recently updated FAOSTAT cattle data in the "Crops and livestock products" domain and Intergovernmental Panel on Climate Change (IPCC) emissions factors (EFs) to estimate enteric fermentation and manure management emissions estimates for years 2015 to 2023.

2. Materials and Methods

The approach employed to estimate country-level cattle operation emissions used the FAOSTAT domain "Crops and livestock products" and the items:

- "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 for 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 beef cattle operations, described further in section 2.2.2.

These two cattle stock items were used to represent cattle in operation at the country-level. Using these cattle types, IPCC EFs and equations from The IPCC 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 2006a; IPCC 2006b). Figure 1 provides an overview of the approach employed for this sector.

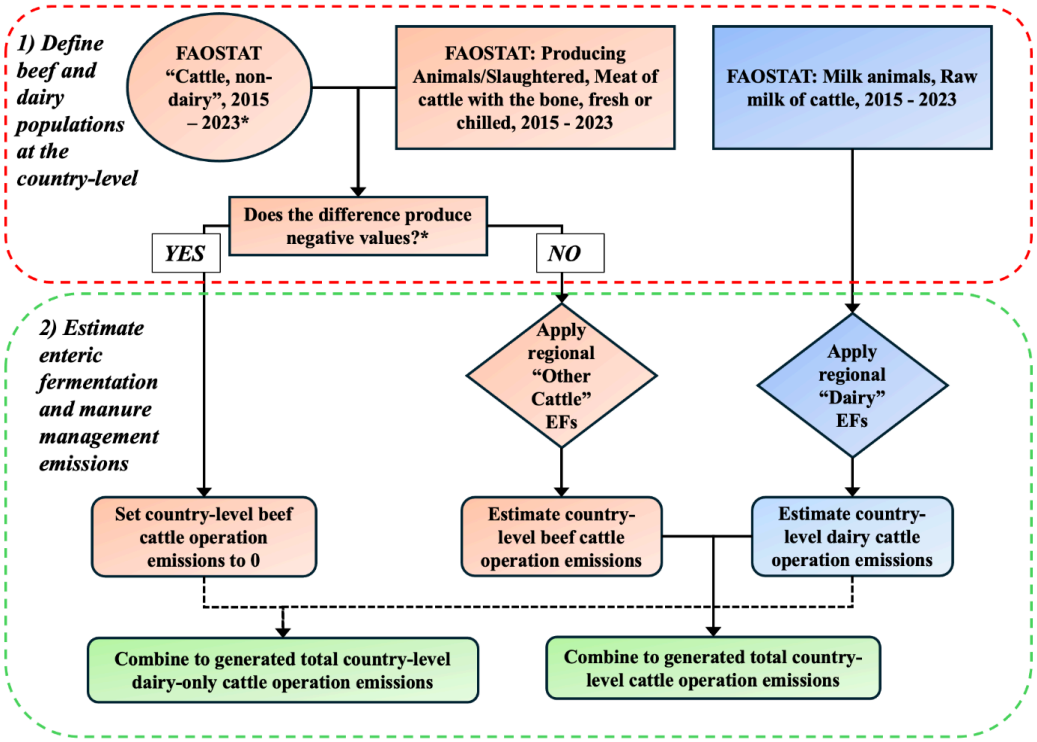

Figure 1 Flowchart depicting the FAOSTAT data used to estimate country-level cattle operations emissions. More information described in text below. An asterisk in certain shapes indicates this step was performed for the *"Agriculture sector- Emissions from Enteric Fermentation and Manure Left on Pasture from Cattle"* and incorporated into this sector to estimate country-level confined emissions.

2.1 Datasets employed

2.1.1 FAOSTAT data

To estimate cattle in operations, 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.

FAOSTAT data for years 2015 to 2022 were accessed with the year 2023 forward-filled with 2022 data. At the time of this study, the "Crops and livestock products" domain was selected since it provided the most recent cattle data, up to date as of December 27, 2023 (accessed June 27, 2024), whereas the domain "Emissions from Enteric fermentation and Emissions from Manure Management" was updated November 9, 2023. Additionally, the more recent version 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).

2.1.2 IPCC emission factors

EFs from The IPCC 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 2006a; IPCC 2006b). Cattle emissions are produced by enteric fermentation, producing CH_4, and manure management, producing CH_4 and N_2O. To estimate CH_4 and N_2O emissions, the IPCC Tier 1 approach was applied with a Tier 2 approach included for Indirect N_2O emissions due to leaching from manure management systems. Due to the lack of detailed manure management systems, assumptions were applied, discussed further in section 2.2.

A modification was made to Table 10A-4 EFS, "Manure Region Management System Usage (MS%)" for regions with "Other" column values. There is no clear explanation to what the "Other" column represents for manure management practices or emissions. Therefore, the "Other" manure management percentage was assigned to the most common, or the highest percentage, manure management system in that region. An example of this is shown in Table 1. As a result, the most dominant manure management system percentage is higher than what was reported in IPCC CH. 10. Lastly, the "Pasture/Range/Paddock" and "Burned for Fuel" categories were not included in the country-level emissions estimates for this sector and were reported in the Climate TRACE sectors "*Emissions from Enteric Fermentation and Manure Left on Pasture from Cattle*" and "other-energy-use" or "Other Energy Use", respectively.

Table 1 An example of adjusting Manure Management System (MMS) Usage (MS%) to include "Other" category type. 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***

Default IPCC “Other Cattle” and “Dairy Cows” EFs based on region, temperature, and manure management systems was applied to “Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled” and “Milk animals, Raw milk of cattle” populations, respectively.

2.2. Methods

2.2.1 FAOSTAT “Crops and Livestock” domain - identifying beef and dairy populations

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 meant for beef production and for dairy production, respectively, in each country.

We opted to not 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 U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (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, FAOSTAT did not report 2021 data at the time of this writing. Note, data used in this table was from an FAOSTAT version March 24, 2023, and values may have changed in 2024.

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. USDA slaughtered population is the summation of "CATTLE, CALVES - SLAUGHTERED" and "CATTLE, GE 500 LBS - SLAUGHTERED". When a given year has a positive difference between FAOSTAT and USDA NASS, it indicates FAOSTAT reported a higher volume of slaughtered beef cattle; negative numbers indicate USDA NASS reported a higher volume of slaughtered beef cattle, and zero values indicate matching reported values. Any non-zero value 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 2024.

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 in some type of operation, i.e., in a feedlot in the USA. For FAOSTAT “Milk animals, Raw milk of cattle”, the reported values were treated as representing cows processed for milk production in some type of operation, i.e., at a dairy farm.

2.2.2 Countries with no beef cattle operations

Some countries had their “Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled” populations set to zero for all years or some years (Table S1). These data were interpreted to mean that no feedlots generated emissions at the country-level. This is due to FAOSTAT reporting “Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled” population larger 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 could have increased the slaughtered population to higher values relative to the “Cattle, non-dairy” population, which may not have been updated to reflect this change. Table 4 provides Ukraine and Egypt as examples of different values being reported. This can be seen in the version updates for “Crops and livestock products” domain updated March 24, 2023, whereas the “Emissions from Enteric fermentation and Emissions from Manure Management” was updated November 4, 2022.

Table 4 Egypt and Ukraine examples of “Milk Animals” compared to “Cattle, dairy” populations (top table) and “Producing Animals/Slaughtered” with larger populations relative to “Cattle, non-dairy” population (bottom table). Negative difference values indicate “Producing Animals/Slaughtered” or “Milk Animals” reporting higher populations than “Cattle, non-dairy” or “Cattle, dairy”. Flags are included with each value: A = Official figure, I = Imputed value, and E = Estimated value. Note, data used in this table was from an FAOSTAT version March 24, 2023, and values may have changed in 2024.

Region	Year	Cattle, dairy	Milk Animals, Raw milk of cattle	Difference
Egypt	2018	1,581,467 (E)	1,582,132 (I)	-665
	2019	1,658,564 (E)	1,739,730 (I)	-81,166
	2020	1,418,355 (E)	1,727,509 (E)	-309,154
Ukraine	2018	1,995,800 (E)	1,995,800 (A)	0
	2019	1,898,300 (E)	1,898,300 (A)	0
	2020	1,765,600 (E)	1,765,600 (A)	0

Region	Year	Cattle, dairy	Milk Animals, Raw milk of cattle	Difference
Egypt	2018	1,581,467 (E)	1,582,132 (I)	-665
	2019	1,658,564 (E)	1,739,730 (I)	-81,166
	2020	1,418,355 (E)	1,727,509 (E)	-309,154
Region	**Year**	**Cattle, non-dairy**	**Producing animals/slaughtered, Meat of cattle with the bone, fresh or chilled**	**Difference**
Egypt	2018	2,797,533 (E)	1,145,000 (A)	1,652,533
	2019	1,150,436 (E)	1,386,000 (A)	-235,564
	2020	993,334 (E)	1,245,000 (A)	-251,666
Ukraine	2018	1,535,000 (E)	2,145,900 (A)	-610,900
	2019	1,434,600 (E)	2,127,500 (A)	-692,900
	2020	1,326,400 (E)	1,987,600 (A)	-661,200

When "Producing Animals/Slaughtered" was higher 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.

2.2.3 Deriving country-level temperature data

Manure management methane emissions are driven by the number of animals and the temperature (IPCC, 2006a). To reflect temperature’s influence, the average annual temperature for each country was produced from the ERA5-Land Monthly Aggregated from the European Centre for Medium-Range Weather Forecasts (ECMWF) Climate Reanalysis via Google Earth Engine (Muñoz Sabater, J., 2019). The specific image collection accessed was “ECMWF/ERA5_LAND/MONTHLY_AGGR”, which provided a monthly “temperature_2m” band. The Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) was modified by Climate TRACE and country boundaries were used to filter each month’s “temperature_2m” values to within each country’s national boundary and averaged to generate annual average temperatures for years 2015 to 2023. Countries with Arctic and subarctic regions (i.e., Canada, Alaska for U.S., and Russia) had their GDAM boundaries slightly modified to not include these regions when estimating the annual average temperatures.

Each country's temperature value was used to determine the IPCC EF to use by year in Table 10.14, "Manure management methane emission factors by temperature" (IPCC 2006a). More information on the GADM employed can be found in the Supplementary section

2.2.4 Estimating country-level emissions

To estimate country-level enteric fermentation CH_4 and manure management CH_4 and N_2O emissions, IPCC equations and default regional "Other Cattle" and "Dairy Cows" EFs were applied to "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" and "Milk animals, Raw milk of cattle" populations, respectively. Table 5 lists the equations used. Once the emissions for each cattle type were calculated, each emission was summed to produce a total country-level.

Table 5 IPCC equations and descriptions for country-level emissions estimates.

IPCC Equation	Description
EQ 10.19	ENTERIC FERMENTATION EMISSIONS FROM A LIVESTOCK CATEGORY
EQ 10.22	CH_4 EMISSIONS FROM MANURE MANAGEMENT
EQ 10.25	DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT
EQ 10.26	N LOSSES DUE TO VOLATILISATION FROM MANURE MANAGEMENT
EQ 10.27	INDIRECT N_2O EMISSIONS DUE TO VOLATILISATION OF N FROM MANURE MANAGEMENT
EQ 10.28	N LOSSES DUE TO LEACHING FROM MANURE MANAGEMENT SYSTEMS
EQ 10.29	INDIRECT N_2O EMISSIONS DUE TO LEACHING FROM MANURE MANAGEMENT

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), 80.8 (20 year) and 27.2 (100 year) 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 20 and 100 year GWPs into total 20 and 100 year GWPs. More information on specific data fields and values are described in the Supplementary section.

Certain countries had their emissions replaced with the N_2O emissions generated from aggregated operations within a country from "*Agriculture sector- Enteric Fermentation and Manure Management Emissions from Cattle Operations*": Argentina, Australia, Brazil, Botswana, Canada, Mexico, and South Africa for various years. USA had both manure management CH_4 and N_2O emissions for years 2020 to 2023 replaced. This change was made to

account for higher resolution, facility-level emissions datasets, also developed by Climate TRACE, which were aggregated within a country and were greater than the FAOSTAT emissions generated. Facility-level data also provided more detailed manure management observations at specific cattle operations which were used to define specific manure management systems, affecting N_2O emissions. Additionally, operation-specific "Manure management methane emission factors by temperature" EFs were used instead of a country-level derived EF, which can lead to higher manure management CH_4 emissions.

Of the 250 countries and administrative regions reported for this sector, 192 had emissions estimated generated for years 2015 to 2023. The remaining 58 countries and administrative regions (i.e., Bermuda, Palau, and Tuvalu) do not report or do not have cattle information in FAOSTAT, and their emissions estimates were set to zero for all years.

3. Discussion and conclusion

By using FAOSTAT cattle information from the "Crops and livestock products" domain and generating emissions from the cattle stocks' items- "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" and "Milk animals, Raw milk of cattle", Climate TRACE produced cattle emissions by type that is more representative of cattle types at operations than reported FAO emissions values. Additionally, the mapping exercise performed in section 2.1.1 identified that FAOSTAT data is not always updating and consistent with data changes with a reporting country. This can create discrepancies in emissions reported depending on the data domain used.

Future work includes identifying the cattle slaughtered for meat production in countries that produced negative differences (section 2.2.1). This can include import/export data to help identify domestically bred and slaughtered cattle. Additionally, updated EFs will be considered to reflect changes in cattle practices in meat and dairy production in different countries. Lastly, to further refine temperature data used for manure management emissions, countries that have spatially distributed cattle density information can be used to obtain temperature values 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. Efforts to better associate average temperatures with specific areas of cattle management will generate more appropriate IPCC emissions factors from Table 10.14, "Manure management methane emission factors by temperature", that better reflects temperature influences on CH_4 manure management emissions.

4. Supplementary metadata section

Table S1 Cattle population 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. The "+" sign indicates years where the "Cattle, non-dairy" population was larger than "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled", meaning these years had a representative beef cattle operations emissions estimated. Negative values indicate years where all "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled" were interpreted to mean that no feedlots generated emissions at the country-level. Note, 2023 was forward filled with 2022 data.

Country \ Year	2015	2016	2017	2018	2019	2020	2021	2022
Albania	-184928	-189751	-202417	-133150	-211613	-217165	-181343	-199254
Armenia	-231319	-243917	-218974	-214788	-215263	-224289	-218468	-221378
Azerbaijan	+	+	-11264	-15137	-28442	-53655	-81707	-67681
Bahamas	-43	-41	-39	-39	-38	-36	-36	-36
Bahrain	-4942	-4384	-3888	-3653	-4040	-3623	-4038	-3831
Brunei Darussalam	-1553	-3875	-4739	-4375	-4244	-7169	-13244	-10207
Hong Kong	-21388	-20441	-20534	-19640	-20588	-20636	-20674	-20655
Egypt	+	+	+	+	-235564	-251666	-24192	-137929
Israel	-21866	-13939	-14484	-13164	-12877	+	+	+
Jordan	-88750	-91915	-86221	-84253	-91662	-94254	-98342	-96298
Lebanon	-189062	-170254	-187708	-180723	-197209	-180913	-177817	-179365
Mauritius	-6556	-6892	-6536	-6458	-6819	-5831	-5906	-5869
Montenegro	+	+	+	+	-1469	-4778	+	+
Netherlands	+	+	+	-104750	+	+	+	+
Palestine	-17472	-24519	-28437	-41090	-24509	-25934	-60787	-43361
Republic of Moldova	-3879	-5640	+	+	+	-4265	+	+
Sao Tome and Principe	-175	-92	-84	-84	-88	-85	-92	-89
Saudi Arabia	-100199	-101238	-102042	+	+	+	+	+
Syrian Arab Republic	+	+	-80590	-115178	-97916	-200074	-200432	-200253
Tunisia	-51896	-51791	-47559	-55415	-58604	-60928	-58568	-59748
Ukraine	-659600	-651500	-588500	-610900	-692900	-661200	-415700	-538450
United Arab Emirates	-3575	-6680	-9414	-10932	-13103	-16611	-18363	-17487

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 2023. 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 S2 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 – 2023*
Temporal Resolution	*Annual*
Data format	*CSV*
Coordinate Reference System	*None. ISO3 country code provided*
Number of countries available for download	*250 countries*
Total emissions for 2023	*Total Enteric Fermentation CH_4 emissions = 36,526,084.50 metric tons* *Total Manure Management CH_4 emissions = 3,552,463.12 metric tons* *Total Manure Management N_2O emissions = 1,151.10 metric tons*
Ownership	*Country*
What emission factors were used?	*IPCC 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"*

General Description	Definition
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*

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Citation format: Davitt, A., Lewis, C., Andoe-Leggett, M., and Schiller, S. (2024). *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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