Agriculture sector-
Cattle Emissions from Enteric Fermentation and Manure Left on Pasture

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1. Introduction

The global cattle industry contributes significantly to greenhouse gas (GHG) emissions through enteric fermentation, a natural digestive process in cows that results in methane (CH_4) release, and manure left on pastures, which produces both CH_4 and nitrous oxide (N_2O) upon decomposition (Dong et al., 2006). The emissions of methane and nitrous oxide from the digestion of livestock and dung must be closely measured, tracked, and monitored. In order to reduce the negative impact that livestock farming has on the environment and climate, scientists, farmers, and policymakers can develop plans or take action (manage and mitigate) by understanding how much greenhouse gas is being generated. Emitted through natural sources and human activities like agriculture and landfills, methane is 25-30 times more potent than carbon dioxide (CO_2) but doesn't stay as long in the atmosphere (U.S. Environmental Protection Agency, 2023). However, nitrous oxide from manure on pasture is about 300 times more potent than CO_2. The animal itself and the surface of the pasture are the two main places where these emissions take place. Microbes in the cattle's rumen use enteric fermentation to break down fibrous plant matter, producing CH_4, which is primarily released by belching (Lynch, 2019). Manure left behind by grazing cattle breaks down on pastures under different oxygen and moisture levels. Anaerobic decomposition generates CH_4 during this process, whereas soil nitrification and denitrification release N_2O (Lynch, 2019). Temperature, soil type, and moisture are examples of environmental conditions that have a significant impact on the amount of these emissions. Grazing systems are a significant source of CH_4 and N_2O in agricultural landscapes due to these combined processes (Rivera et al., 2024; Rivera & Chará, 2021). Current methods in reporting cattle pasture emissions include FAOSTAT estimation by following the Tier 1 method of IPCC 2006 emission factors (FAO, 2022; Tubiello et al., 2013). FAOSTAT estimated cattle enteric fermentation and manure management emissions at a country level by applying emission factors to the number of cattle. Except for N_2O emissions from manure left on pastures, they did not focus on cattle pasture emissions since their estimate included all cattle in the country. There is also a difference in the scope of their work in that they did not spatially disaggregate the emissions beyond the country level. Some novel methods include training and machine learning

ML model on Sentinel-2 satellite imagery and biomass measurement data (Chen et al., 2021). After using model inference on other satellite images to determine pasture cattle, emission factors were applied to obtain GHG emissions. Since the study was limited to only 5 farms in Tasmania, further evaluation across more diverse regions and pasture types is still needed. Although the initial results seem promising, they still need to be validated more extensively before the methodology can be deployed operationally.

We developed Climate TRACE Pasture-Cattle Emissions Inventory version 2, a new methodology based on the IPCC 2019 Tier 2 framework. This version builds upon the 2021 Climate TRACE Pasture-Cattle Emissions Inventory (Brown et al., 2024), which was developed using the IPCC 2006 Tier 1 approach. By calculating methane (CH_4) emissions from gross energy intake (GEI) and adding climate-specific methane conversion factors (MCFs) and manure-management system (AWMS) fractions, this update enhances scientific realism and spatial accuracy. More flexible and transparent calculation of cattle-on-pasture emissions is made possible by the Tier 2 model, which also explicitly depicts direct and indirect nitrous oxide (N_2O) pathways and permits parameterization based on nation and climate. Cattle populations were estimated by subtracting slaughtered animals from total non-dairy cattle (FAO, 2022, 2023), then downscaled using pasture area fractions from SEDAC (Socioeconomic Data and Applications Center) satellite-derived product (Ramankutty et al., 2010). Climate zones were assigned using the Climatic Research Unit gridded Time Series (1991–2020) and IPCC thresholds. Emissions were calculated using IPCC 2019 which allow for differentiation by cattle maturity and region.

This methodology describes the approach to estimate cattle emissions from enteric fermentation and manure left on pastures. We present a global 0.083° × 0.083° Tier 2-based assessment of enteric and manure CH_4 and manure N_2O emissions from non-dairy pasture cattle for years 2015–2024. Furthermore, beginning November 2025, Climate TRACE is providing potential emission reduction solutions (ERSs) to understand how sector specific mitigation strategies can reduce emissions for this sector.

2. Materials and Methods

We assembled country livestock statistics (FAO, 2022, 2023), climate and terrain descriptors (CRU TS, GMTED2010)(Danielson & Gesch, 2011; Harris et al., 2020; Harris et al., 2023), and satellite‑derived pasture fractions (NASA SEDAC) with administrative boundaries (GADM) to map non-dairy cattle on pasture globally (GADM, 2022; Ramankutty et al., 2010). Using the IPCC 2019 Tier 2 methodology (2019 IPCC Ch10 and Ch11) (Gavrilova et al., 2019; Hergoualc'h et al., 2019), we compute pixel-level CH_4 (enteric, manure) and N_2O (manure on pasture) emissions with region- and climate-specific parameters, then aggregate to country totals. Outputs include GeoTIFF rasters and country-level CSV tables for 2015–2024, with accompanying uncertainty layers. The datasets were generated in the European Petroleum

Survey Group (EPSG) reference frame 4326 (EPSG: 4326), which is a EPSG database registry for the World Geodetic System 1984 (WGS 84) datum.

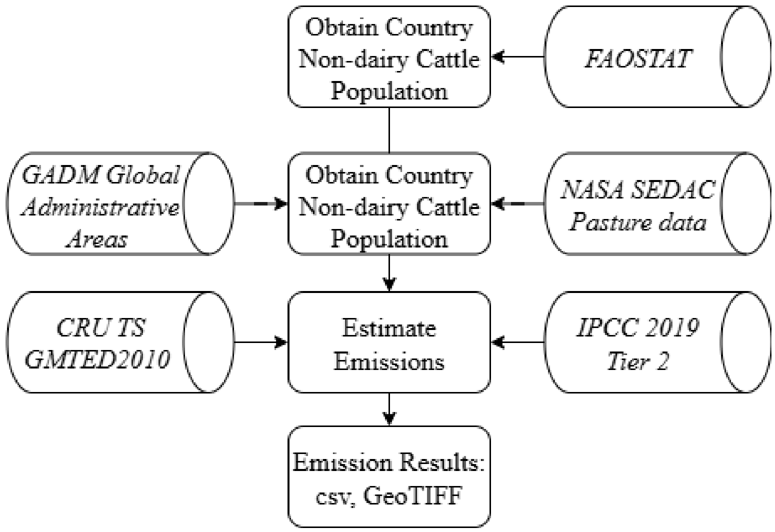


Figure 1 *Methodology Flowchart to estimate emissions from cattle on pasture based on IPCC 2019 Tier 2.*

Our primary goal was to generate high-resolution GeoTIFF datasets in EPSG 4326 (WGS84) for CH_4 and N_2O emissions from manure on pasture and enteric fermentation, along with their corresponding global warming potentials (GWPs), for the years 2015–2024. These outputs were produced using the IPCC 2019 Tier 2 methodology with region- and climate-zone-specific parameters. In addition to the raster outputs, country-level aggregated results were compiled into CSV tables, providing annual estimates for emissions, emission factors, capacities, and capacity factors. Uncertainty layers were also generated for each sector and gas in both raster and tabular formats.

We utilized pandas, geopandas, and the rasterio library to create the GeoTIFFs and organize the data from various sources. It is important to note that our work was not inclusive of all enteric fermentation and manure management GHG emission estimation, but rather those that come from cattle on pasture only. This is different from FAOSTAT which reports all dairy and non-dairy populations in both domains "Emissions from Manure Management" and "Manure left on pasture", creating overlap between the two (FAO, 2022, 2023). In this work, we seek to create a more representative cattle population that exists on pasture only. As such, Climate TRACE reports separately dairy and feedlot enteric fermentation and manure management emissions at the country level and for individually identified feedlots and dairies. These approaches can be found in the cattle methodologies in our GitHub repository.

2.1 Datasets employed

To generate the datasets, we used five data sources. These five were the following: Food and Agriculture Organization Corporate Statistical Database (FAOSTAT)(FAO, 2022, 2023), Global Administrative Areas (GADM, 2022), Climatic Research Unit gridded Time Series (CRU TS)(Harris et al., 2023), digital elevation model and NASA Socioeconomic Data and Applications Center (SEDAC)(Ramankutty et al., 2010). First, we used FAOSTAT to determine the total number of non-dairy cattle and slaughtered cattle for each country under the item using "Meat of cattle with the bone, fresh or chilled" from the "Crops and livestock products" domain and item "Cattle, non-dairy" from "Emissions from Livestock" domain (https://www.fao.org/; datasets accessed in August of 2024). Individual countries report this data directly to FAOSTAT. Compared to FAOSTAT data used in the previous version, which relied on IPCC 2006 Tier 1 approach (Brown et al., 2024), we used the most recently updated FAOSTAT data for slaughtered cattle and non-dairy cattle, datasets are available for the years 2015-2023. Holt's linear exponential smoothing method was used in estimated cattle data for 2024 (Gardner Jr, 1985). Holt's linear exponential smoothing is a time-series forecasting method that accounts for both the current level and the trend of the data. Because it catches upward or downward trends rather than assuming values stay constant, it typically yields more accurate projections than straightforward techniques (such as a simplified use of the year mean). Because it is a smoothing-based method rather than a data-hungry one, it can function effectively even with small datasets (5–10 years), as cattle data from 2015–2023.

30-year monthly frost days, potential evapotranspiration, precipitation, and temperature data from CRU TS (0.5° x 0.5°) and Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) (Danielson & Gesch, 2011), were used for creating 12 climate zones based on IPCC Guidelines Refinement 2019 threshold. The IPCC 2019 Refinement delineates 12 global climate zones based on long-term averages meteorological data above mentioned, while also accounting for elevation effects that modify local thermal and moisture conditions. High-altitude regions are classified into distinct montane or highland zones within the tropical and temperate categories to better represent climatic gradients influencing livestock productivity and manure decomposition. This stratification enables the application of region-, climate-, and elevation-specific emission parameters, thereby improving the spatial accuracy of Tier 2 greenhouse gas estimates.

Next, we used NASA SEDAC pasture data which provides a pastureland area percentage for each 0.083° × 0.083° degree square (~10km at the equator) represented as GeoTIFF pixels in the world for the year 2000 (Figure 1). This data was obtained by applying machine learning to satellite imagery to determine the type of land area in each square (Ramankutty et al., 2010). Although the dataset was generated for the year 2000, it was used to estimate emissions for the years 2015 - 2022.

Finally, GADM data was used to obtain country boundaries for mapping the SEDAC pasture area to a country. The GADM boundary dataset was formatted as a geojson provided by WattTime.

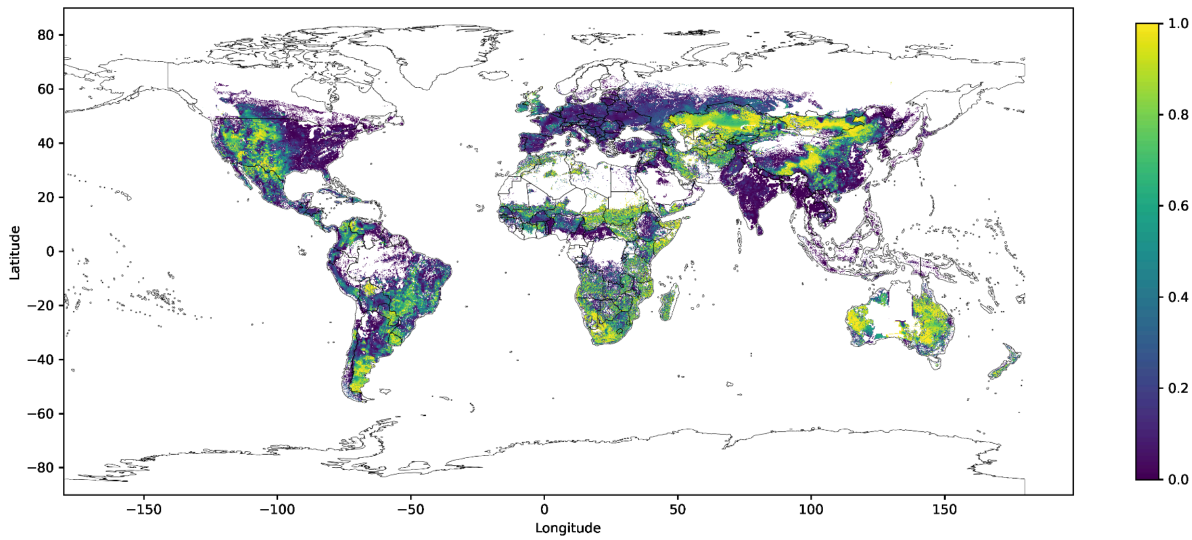


Figure 2 *NASA SEDAC Pasture fraction (%) data for the year 2000.*

2.2 Methods

2.2.1 Cattle Disaggregation

In order to establish a transparent and reproducible framework for estimating greenhouse gas emissions from non-dairy cattle on pasture, it is necessary to introduce the concepts of capacity, capacity factor, and activity. These terms provide a structured link between national livestock statistics, spatial land-use data, and the IPCC's methodological requirement that emissions be calculated as the product of activity data and emission factors.

- Capacity represents the total number of non-dairy cattle on pasture reported at the national scale, thereby defining the reference population available for allocation.
- Capacity factor expresses the relative share of pasture within each spatial grid cell, normalized across all eligible cells (country level) so that the sum of factors equals one, ensuring that spatial distribution is proportional to available grazing land.
- Activity then denotes the number of cattle allocated to each grid cell, calculated as the product of national capacity and the cell-specific capacity factor.

This three-part formulation is essential because it guarantees that the spatial distribution reconciles exactly with official livestock inventories, thereby maintaining mass balance and consistency across scales. Moreover, it enhances transparency by explicitly documenting the allocation mechanism, while preserving flexibility for methodological refinements, such as incorporating forage productivity, pasture functional diversity, stocking rates, or climate constraints into the capacity factor. Framing the approach in terms of capacity, capacity factor, and activity not only aligns with the IPCC 2019 guidelines but also facilitates comparability and repeatability of results, ensuring that emission estimates are robust, traceable, and scientifically defensible.

For estimating any emissions arising from non-dairy cattle on pasture (also defined as Capacity), the first necessity is to obtain pasture cattle spatially. The goal is to distribute country-level cattle numbers from FAOSTAT to the WGS84 grid based on the pastureland area provided by NASA SEDAC.

Step 1: Subtracting slaughtered cattle ensures that emissions derived "pasture cattle" count represents the living, emitting, pasture-based herd, which is the correct population to use when distributing emissions spatially and computing enteric/manure CH_4 and N_2O using IPCC Tier 2 equations. To obtain the total number of cattle in the pasture area by subtracting the count of slaughtered cattle from the total non-dairy count for each year for each country using the equation below.

$$Total\ cattle\ on\ pasture_t = Cattle, NonDairy_t - Producing\ Animals/Slaughtered_t$$

Where for each year, "*t",* the "*Cattle,NonDairy*" and "*Producing Animals/Slaughtered*" for that year were subtracted from each other because it was assumed slaughtered were not on pasturelands and in a cattle operation of some type. The "*Cattle,NonDairy*" and "*Producing Animals/Slaughtered*" were the "Cattle, non-dairy" and "Producing Animals/Slaughtered, Meat of cattle with the bone, fresh or chilled", respectively (https://www.fao.org/), as described above.

Note that for country-year pairs that resulted in negative values from the equation above, the total number of slaughtered cattle was set to the total cattle on pasture. We found some countries with negative values for cattle on pasture: Albania, Armenia, Bahamas, Bahrain, Brunei Darussalam, China (Hong Kong SAR), Faroe Islands, Israel, Jordan, Lebanon, Mauritius, Palestine, Republic of Moldova, Sao Tome and Principe, Saudi Arabia, Tunisia, Ukraine, United Arab Emirates, Azerbaijan, Syrian Arab Republic, Netherlands, Egypt, Montenegro, and Morocco. These countries generally have limited pasture area, and most are located in arid or densely populated regions where beef consumption is higher than cattle farming (Bernadaux, 2021; Hocquette et al., 2018). Some are small or special administrative regions with minimal or no grazing land.

Step 2: Using SEDAC pasture area percentage for each 0.083° × 0.083° degree polygon, we obtained the world grid of polygons with their respective pasture cover percentage as a pandas dataframe.

Step 3: We obtained grid polygons and the polygons for each GADM boundary to map country name to polygon by finding overlapping polygons between the two sets.

Step 4: then the total cattle on pasture was spatially disaggregated to global pasture data based on the pastureland percentages. For each polygon from SEDAC, the following was performed:

- Obtain the pasture area in each polygon
$$polygon_{pasture\_area} = polygon_{total\_area} * polygon_{pasture\_percentage}$$
- Sum the pasture areas for each country c and N is the set of pixels in the country.
$$total^{c}_{area} = \sum_{N}^{i} polygon^{i}_{pasture\_area}$$
- Divide the polygon's pasture area by its country's pasture area sum to get the pixel's pasture percent of the country as a Capacity factor.
$$polygon_{factor} = polygon_{pasture\_area} / total^{c}_{area}$$
- Then multiply the SEDAC polygon's factor by its country's total assets to obtain the total number of cows in the pixel which define as Activity.
$$polygon_{activity} = polygon_{factor} * country_{assets}$$

2.2.2 Estimation of Emissions from Enteric Fermentation and Manure Left on Pasture

Now that we have spatially distributed pasture cattle, emission factors were applied using IPCC 2019 Chapter 10 and Chapter 11: Emissions from Livestock and Manure Management tier 2 method equations. All CH_4 and N_2O emissions were first calculated at the finest spatial resolution available, based on FID-linked cattle population data in a high-resolution gridded dataset. Each FID corresponds to a pixel in the global livestock distribution layer, containing cattle counts stratified by category, region, and climate zone. Emissions were estimated using the IPCC 2019 Refinement to the 2006 Guidelines (Volume 4: Agriculture, Forestry and Other Land Use), specifically Chapter 10 (Emissions from Livestock and Manure Management) and Chapter 11 (N_2O Emissions from Managed Soils and Livestock Manure Management)(De Klein et al., 2006; Dong et al., 2006). We implemented the Tier 2 methodology, which significantly enhances accuracy and flexibility compared to Tier 1 by deriving methane (CH_4) emission factors from gross energy intake (GEI) rather than fixed look-up tables, thereby accounting for differences in cattle weight, growth rate, and feed quality. The Tier 2 approach also integrates climate-zone-specific methane conversion factors (MCFs) and Animal Waste Management System (AWMS) fractions to reflect real-world manure-management conditions—where pasture systems produce less CH_4 than liquid-based systems such as lagoons. Nitrous oxide (N_2O) emissions are similarly refined through explicit separation of direct (EF_3) and indirect (EF_4, EF_5)

pathways, improving transparency and adaptability across climates and management types. Region- and climate-specific parameters—including body weight, digestible energy, B_0, MCFs, and nitrogen excretion rates (N_{ex})—were applied at pixel level and aggregated to national totals. A detailed description of the Tier 2 equations, parameter sources, and computational workflow for enteric CH_4, manure CH_4, and manure N_2O is provided in Supplementary Section.

The workflow produced two complementary output formats:

1. Raster outputs (GeoTIFF, EPSG 4326) – Pixel-level CH_4 and N_2O emissions and corresponding global warming potentials (GWPs), along with uncertainty layers for each sector, gas, emission factor, capacity, and capacity factor.
2. Country-level tabular outputs (CSV) – Aggregated annual totals for each gas, sector, and associated parameters by country, obtained by spatially joining pixel-level results with national boundaries and summing values.

This dual-format approach ensures both high-resolution spatial mapping and compatibility with national inventory reporting.

The Global Warming Potential (GWP)

The GWP is a metric used to quantify the impact of GHG emissions on global warming. It measures the relative warming potential of different gases over specific time periods, usually 20 and 100 years, considering their radiative forcing effects and atmospheric lifetimes. GWP is crucial because it helps us understand and compare the contributions of various greenhouse gases to climate change. Specifically, for enteric fermentation and manure management, GWP calculations are essential in assessing the environmental impact of these practices, as they involve methane and nitrous oxide emissions. By applying GWP calculations with consideration of uncertainty factors, we can better comprehend the significance of these emissions in the context of climate change mitigation efforts.

To calculate the GWP for enteric fermentation and manure management over different time horizons, we use the following formulas across the Climate Trace coalition:

For a 20-year time horizon:

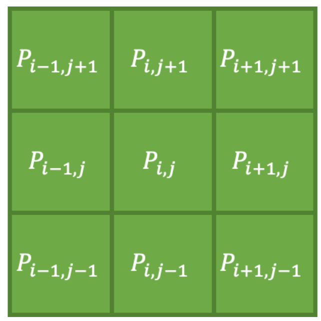
$$GWP\ 20\ year\ =\ CH4\ Emissions\ *\ (80.8 \pm 25.8)\ +\ N2O\ Emissions\ *\ (273 \pm 118)$$

For a 100-year time horizon:

$$GWP\ 100\ year\ =\ CH4\ Emissions\ *\ (27.2 \pm 11)\ +\ N2O\ Emissions\ *\ (273 \pm 130)$$

Estimating Uncertainties

We define capacity as the area of a grid cell that is pastureland. Capacity factor is the total number of cows in the grid cell. The grid cell is each 1 degree by 1 degree area. Emissions uncertainty is a special case where the upper and lower bound use the lowest uncertainty values of capacity, capacity factor, and emissions factors. Emission factors have a 20% uncertainty, and the capacity has a 20% according to the IPCC (Dong et al., 2006). To obtain the capacity factor uncertainty, we use convolution to assess the amount of variance around a particular grid cell. This is illustrated in Figure 3.



$$\bar{P} = \frac{\sum_i \sum_j P_{ij}}{9}$$

$$\text{Var } P = \frac{\sum_i \sum_j \left(\bar{P} - P_{ij}\right)^2}{9}$$

Figure 3 *Capacity uncertainty calculation*

2.3 Verifying modeled emissions estimates

The GeoTIFFs outputs were verified by making sure the sums of all the data frames in Pandas would equal the sum for the values in the GeoTIFFs. The max was also always greater than the minimum and vice versa. The new datasets were also compared with previous Climate Trace changes year over year.

2.4 Model Generated Outputs

The model outputs GeoTIFF files conforming to EPSG 4326 (WGS84, 2004) for manure on pasture and enteric fermentation GHG emissions and global warming potentials for the years 2015-2023. To assess the uncertainty in emissions, emission factor, capacity, and capacity factor for both sectors' GHGs, another set of GeoTiffs was generated.

Below is an outline of the structure of the model-generated outputs:

- Enteric Fermentation
    - CH_4
        - Emissions Estimate
        - Upper bound for emissions uncertainty
        - Lower bound for emissions uncertainty
        - Emission factor uncertainty
        - Capacity Uncertainty
        - Capacity Factor Uncertainty
    - GWP 20 years
        - Upper bound for emissions uncertainty

        - Lower bound for emissions uncertainty
    - GWP 100 years
        - Upper bound for emissions uncertainty
        - Lower bound for emissions uncertainty
- Manure Management
    - CH_4
        - Emissions Estimate
        - Upper bound for emissions uncertainty
        - Lower bound for emissions uncertainty
        - Emission factor uncertainty
        - Capacity Uncertainty
        - Capacity Factor Uncertainty
    - N_2O
        - Emissions Estimate
        - Upper bound for emissions uncertainty
        - Lower bound for emissions uncertainty
        - Emission factor uncertainty
        - Capacity uncertainty
        - Capacity factor uncertainty
    - 20 year GWP
        - Upper bound for emissions uncertainty
        - Lower bound for emissions uncertainty
    - 100 year GWP
        - Upper bound for emissions uncertainty
        - Lower bound for emissions uncertainty

2.5 Emissions Reduction Solutions Overview and Application

Emissions Reduction Solutions (ERSs) for this sector are broken down by the following:

- Enteric fermentation strategy: include feed additives in cattle diet;
- Manure left on pasture strategy: perform pasture rotation and nitrogen reducing fodder crops.

An additional strategy, silvopastural rotation, is applied to both to reduce emissions. All are discussed below. *Note: Only rank 1 strategies are provided for assets on the Climate TRACE website and additional strategies will be made available in future releases.*

Enteric fermentation- Feed additives in cattle diet

Introducing feed additives into cattle diets offers a promising approach to reducing methane emissions from enteric fermentation in pasture-raised livestock. These additives are methane-inhibiting, acting to reduce the bacteria responsible for producing methane during digestion, thereby lowering emissions. Studies have demonstrated that methanogenesis inhibitors and haloform-containing compounds such as 3-nitrooxypropanol (3-NOP) can reduce methane production by an average of 37% without negatively affecting animal performance. However, due to challenges in ensuring sufficient intake by cattle grazing on pasture or rangeland, the approach assumes that only 50% of cattle in a given pasture can be effectively dosed (Meo-Filho et al., 2024).

Adoption of feed additives has occurred in several countries, including the EU, the United States, and Brazil, primarily to enhance beef weight gain or milk production, with reduced methane emissions as a secondary benefit. Global uptake remains limited, constrained by regulatory restrictions in some countries, implementation costs, potential impacts on product pricing and quality, limited farmer familiarity with the additives, and consumer skepticism (Meo-Filho et al., 2024). Despite these challenges, feed additives represent a scientifically validated, scalable intervention for mitigating methane emissions from ruminant livestock.

Manure left on pasture- Pasture rotation and nitrogen reducing fodder crops

Manure left on pastures by grazing cattle is a source of methane and nitrous oxide emissions, accounting for approximately 0.60% of global emissions. A viable strategy to reduce these emissions is the use of pasture rotation combined with nitrogen-reducing fodder crops. Rotating herds between multiple pastures allows the land to recover between grazing periods, increases soil carbon storage, and improves feed efficiency. Additionally, incorporating specific fodder crops such as plantain can reduce N_2O emissions from urine and dung deposited by grazing animals. Studies indicate that pasture rotation can reduce methane emissions by 18% within two years and achieve a 35% reduction in subsequent years, with a 10-year average reduction of 31.8% assumed for this strategy. For nitrous oxide emissions, reductions of 30–40% have been observed, and a 33% reduction is assumed here. Rotational grazing practices are widely adopted in the United States, with specific incentives available to encourage implementation (Box et al., 2016; Dalgaard, 2019; Kellogg Biological Station, 2018; U.S. Environmental Protection Agency, 2025).

Enteric fermentation and manure left on pasture- Silvopastural rotation

Silvopastoral systems provide a strategy to reduce methane emissions from the digestive systems of pasture-raised cattle. Silvopastural systems integrate multiple vegetation types into pasture areas, allowing for intensive rotational grazing while ensuring adequate resting periods and optimizing forage use. Incorporating specific fodder crops, such as plantain, can additionally reduce nitrous oxide (N_2O) emissions. The approach enhances productivity while lowering the environmental impact of livestock operations. Studies have demonstrated that intensive silvopastoral systems can reduce methane from enteric fermentation by approximately 18% and manure-related methane emissions by 23% (MDPI, 2023; Springer, 2023).

Adoption of silvopastoral systems has been implemented in countries such as Colombia, Brazil, and Mexico. In these contexts, the systems have been used to combine high-quality forage with rotational grazing management, supporting both animal productivity and emissions reductions. However, successful adoption may require technical support for farmers to convert conventional pasture land into silvopastoral systems, and the approach may not be suitable in all regions due to ecological or management constraints (FAO, 2023).

3. Results

We provide GeoTIFFs for pasture cattle distribution, uncertainties, and emission estimates for enteric fermentation and manure management. The spatially explicit maps of Tier 2 emission estimates for 2024 that show the fluxes of nitrous oxide (N_2O) and methane (CH_4) across worldwide pasture regions are shown in Figures 4-6. With greater values centered in tropical and subtropical zones where both cattle density and feed digestibility are higher, these maps demonstrate stark regional differences in emission intensities.

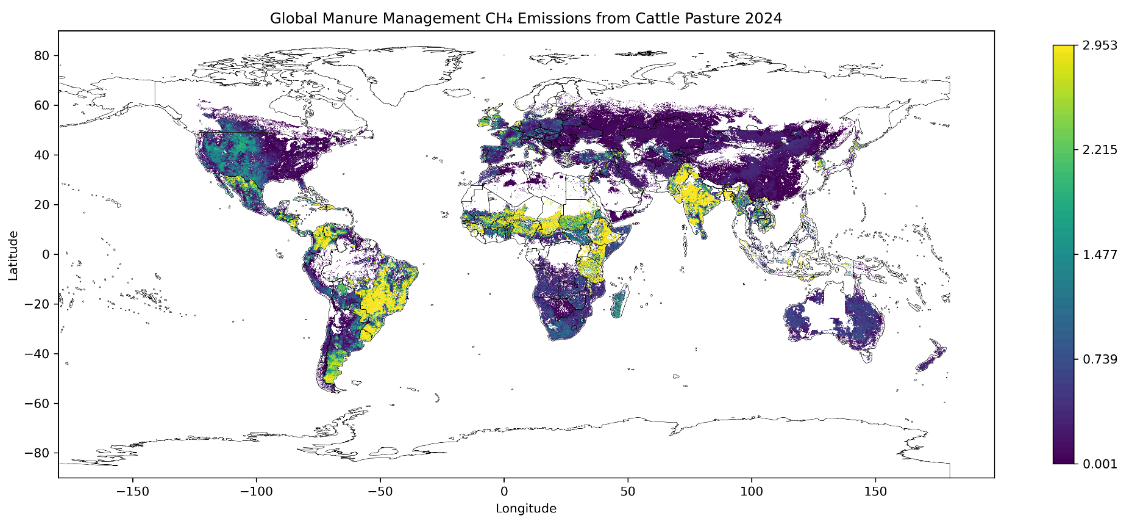


Figure 4 *Manure Management CH_4 Estimates 2024.*

The CH_4 emissions from manure management are shown in Figure 4 and exhibit comparable regional trends, peaking under humid and hot conditions that promote the anaerobic breakdown of volatile materials (Parkinson et al., 2004). On the other hand, emissions are still rather low in temperate and arid areas (such as northern Europe, western North America, and Australia).

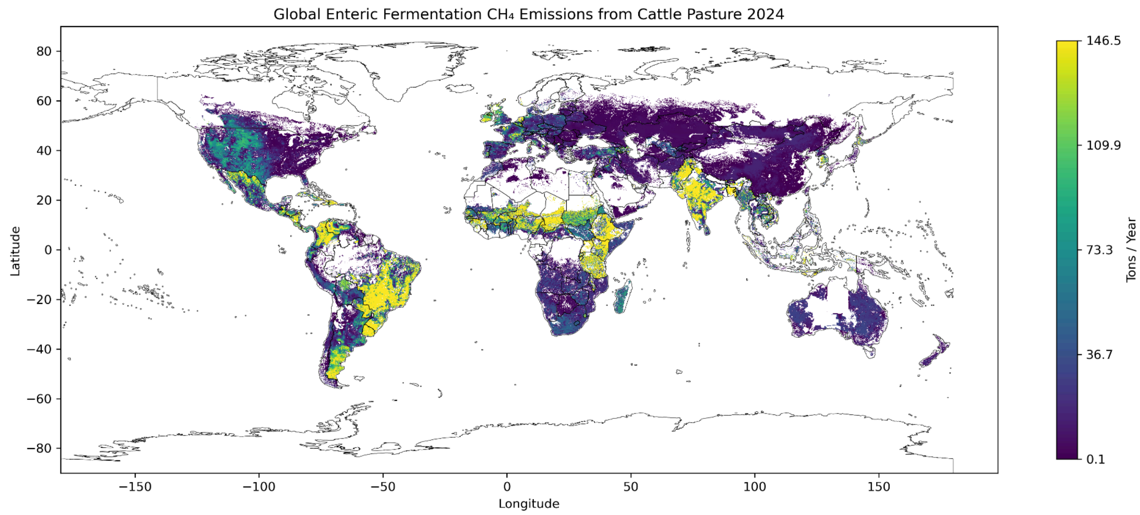


Figure 5 *Enteric Fermentation CH_4 2024.*

CH_4 emissions from enteric fermentation, which account for the majority of pasture-based emissions worldwide, are seen in Figure 5. Major cattle-producing regions including the Indo-Gangetic Plains, the Sahel, the Brazilian Cerrado, and the U.S. Great Plains are examples of high-emission hotspots, with localized annual emissions over 140 tons CH_4 yr^{-1} per grid cell.

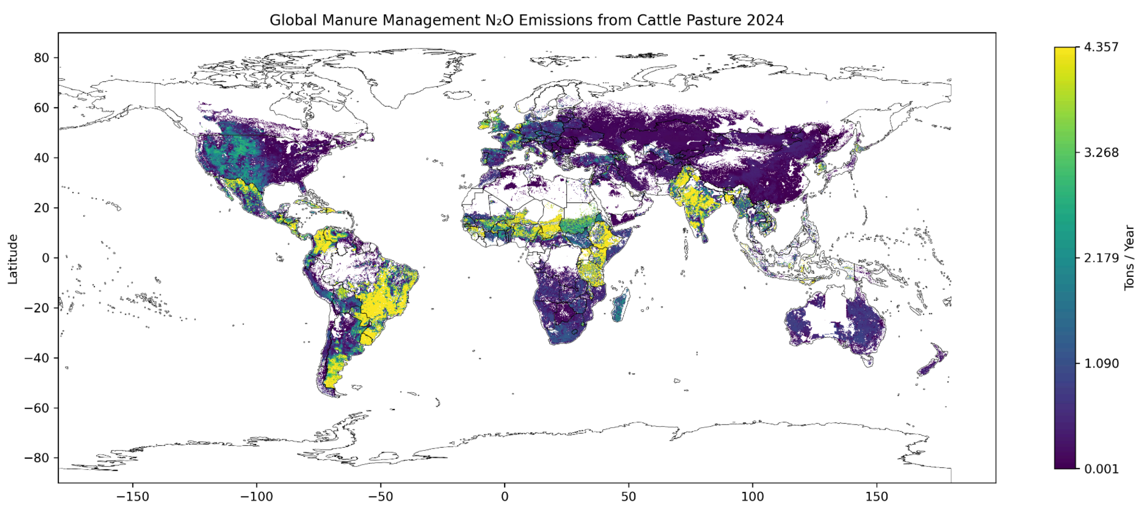


Figure 6 *Manure Management N_2O 2024.*

Figure 6 shows that the regions with the highest manure management N_2O emissions are tropical Latin America, Sub-Saharan Africa, and portions of South and Southeast Asia. These regions are characterized by warm temperatures and high rates of nitrogen excretion. In localized locations with dense cow populations, especially in Brazil and India, emission intensities over 4 tons N_2O yr^{-1}.

Under Tier 2 methodology, the temporal trends of global emissions (Figure 7) show a steady rising trend for all three GHG components cattle emissions from enteric fermentation and manure left on pasture. Between 2015 and 2024. Over the course of ten years, the global emissions of CH_4 from enteric fermentation rose from roughly 51.0 to 56.9 Mt CH_4 yr^{-1}, or an increase of about ~ 11%. The emissions of manure management CH_4 grew from 1.00 to 1.11 Mt CH_4 yr^{-1} (about ~ 10% increase), while the emissions of manure N_2O increased from 1.45 to 1.60 Mt N_2O yr^{-1} (approximately 10.3% increase). These consistent rises are a result of the increase of the world cattle population. Short-term variations in cattle population, possibly related to global commerce and climatic impacts.

Regional dominance is evident in emission patterns at the national level (Figure 8). Together, Brazil, India, the United States, Ethiopia, and Argentina are the top five countries that release enteric fermentation CH_4, which accounts for near half of all emissions from pasture cattle worldwide. Because of their vast herds of cattle and tropical climate, Brazil and India are always at the top. India and Brazil, on the other hand, have comparatively greater manure management CH_4 and N_2O emissions, whereas Ethiopia and Argentina have smaller but increasing contributions.

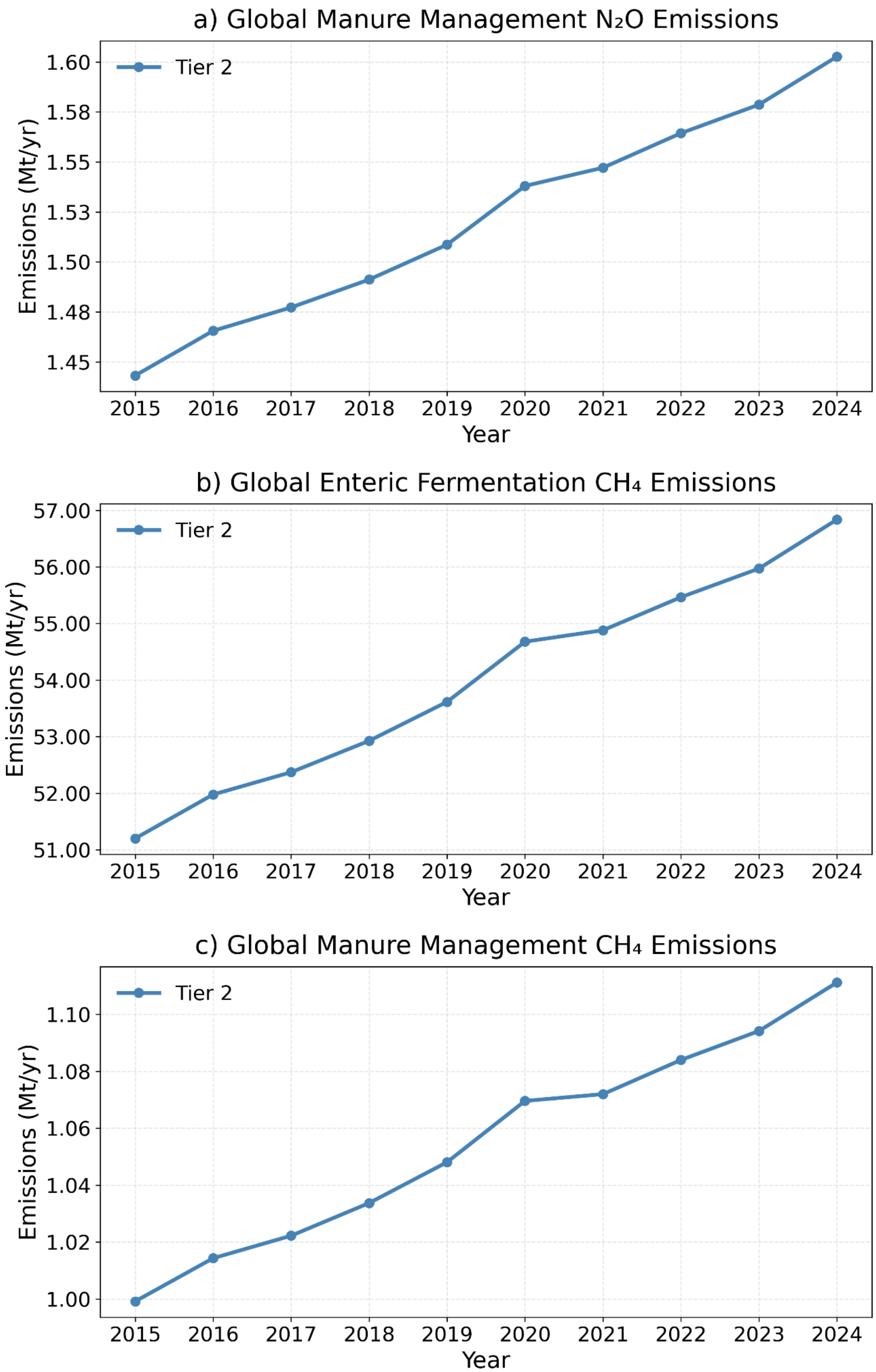


***Figure** 7 Line Charts of Global Emission Estimations Tier 2 (upper row) methods. Left graph, manure management N2O emissions; Center graph, enteric fermentation CH_4 emissions; Right graph, manure management CH_4 emissions.*

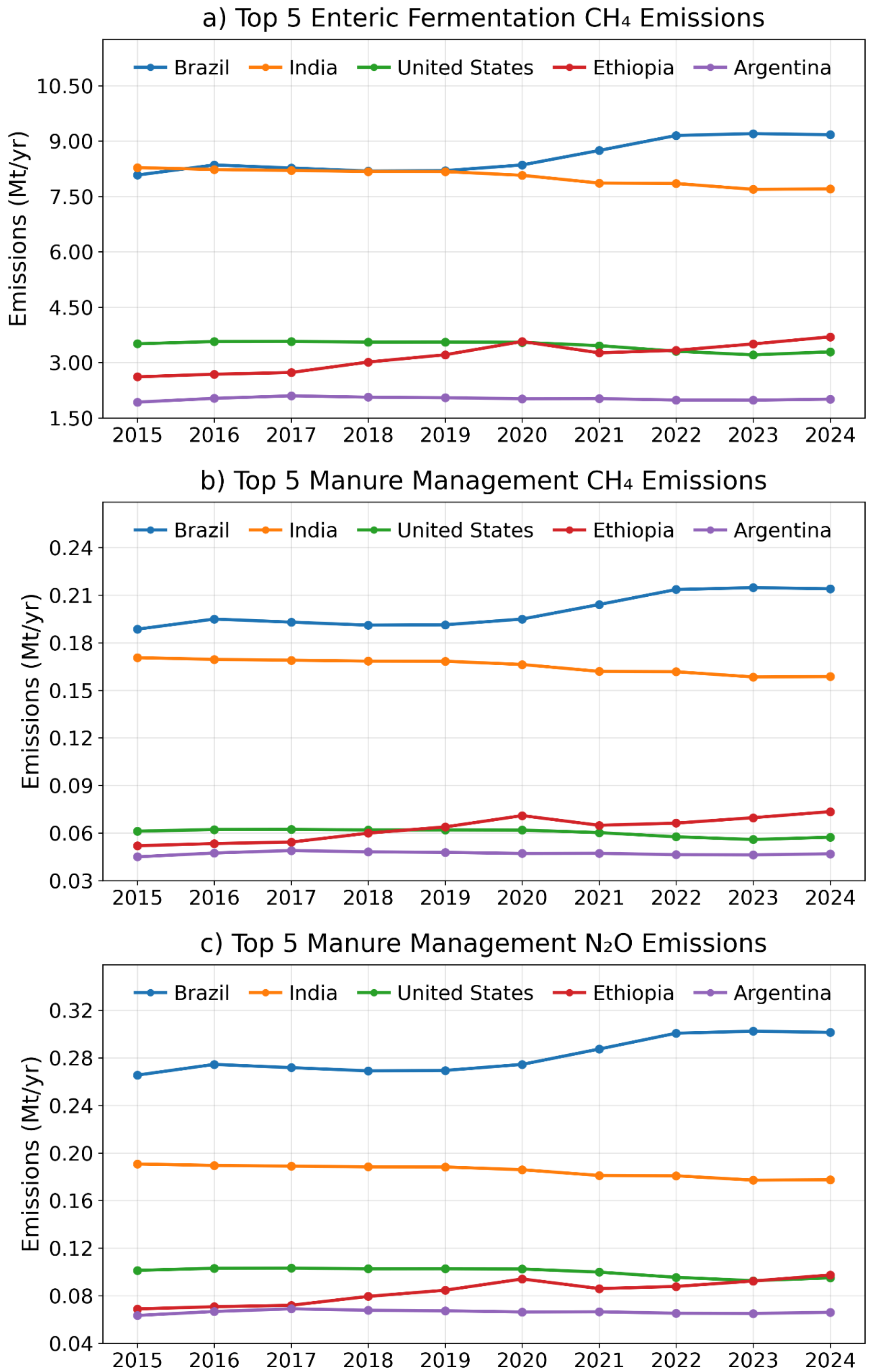


Figure 8 *Line Charts of Top 5 Emitting Countries from Tier2 methods during 2015-202. Left graph, enteric fermentation CH_4 emissions; Center graph, manure management N2O emissions; Right graph, manure management CH_4 emissions.*

4. Discussion

Figure 9 presents the top ten countries ranked by absolute pasture area and by the proportion of national territory classified as pasture, based on the SEDAC pasture dataset. Large land-rich countries such as Australia, China, the United States, and Brazil dominate in terms of total area, while smaller countries such as Mongolia, Chad, and Sudan appear more prominently when considering relative share. These rankings reflect the spatial distribution of mapped pasture rather than actual livestock populations. Figure 9 also indicated that, it is important to acknowledge the limitations of the pasture dataset: the underlying satellite-derived data was generated in 2000, remains static across subsequent years, and is labeled with low confidence, meaning that while it provides useful context on the distribution of pastureland, it may not fully capture present-day dynamics relevant to methane emissions.

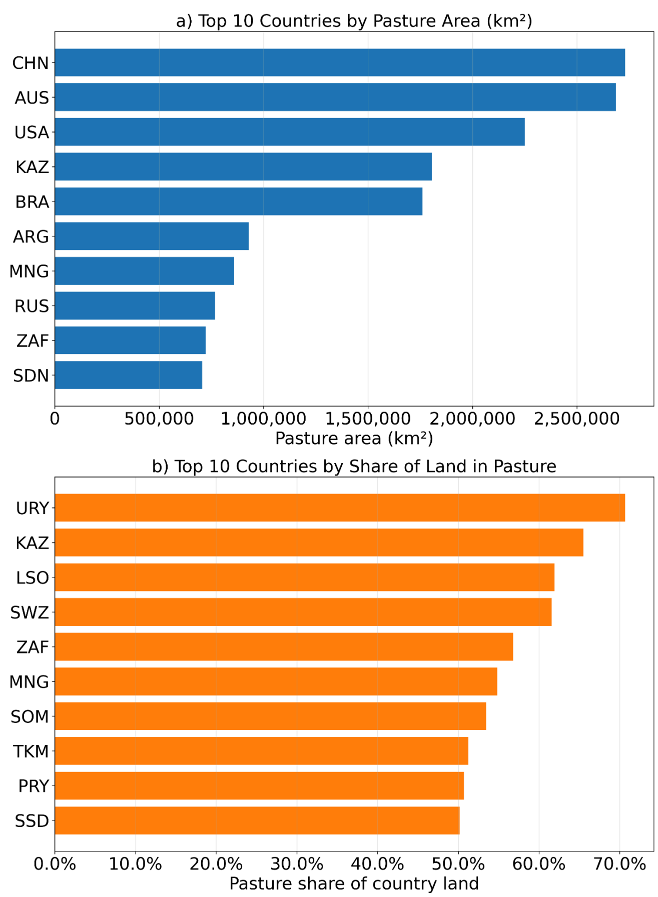


Figure 9 *a) Top 10 countries by absolute pasture area (km²) and b) Top 10 countries by relative share of national land devoted to pasture (%), both are based on Pasture data.*

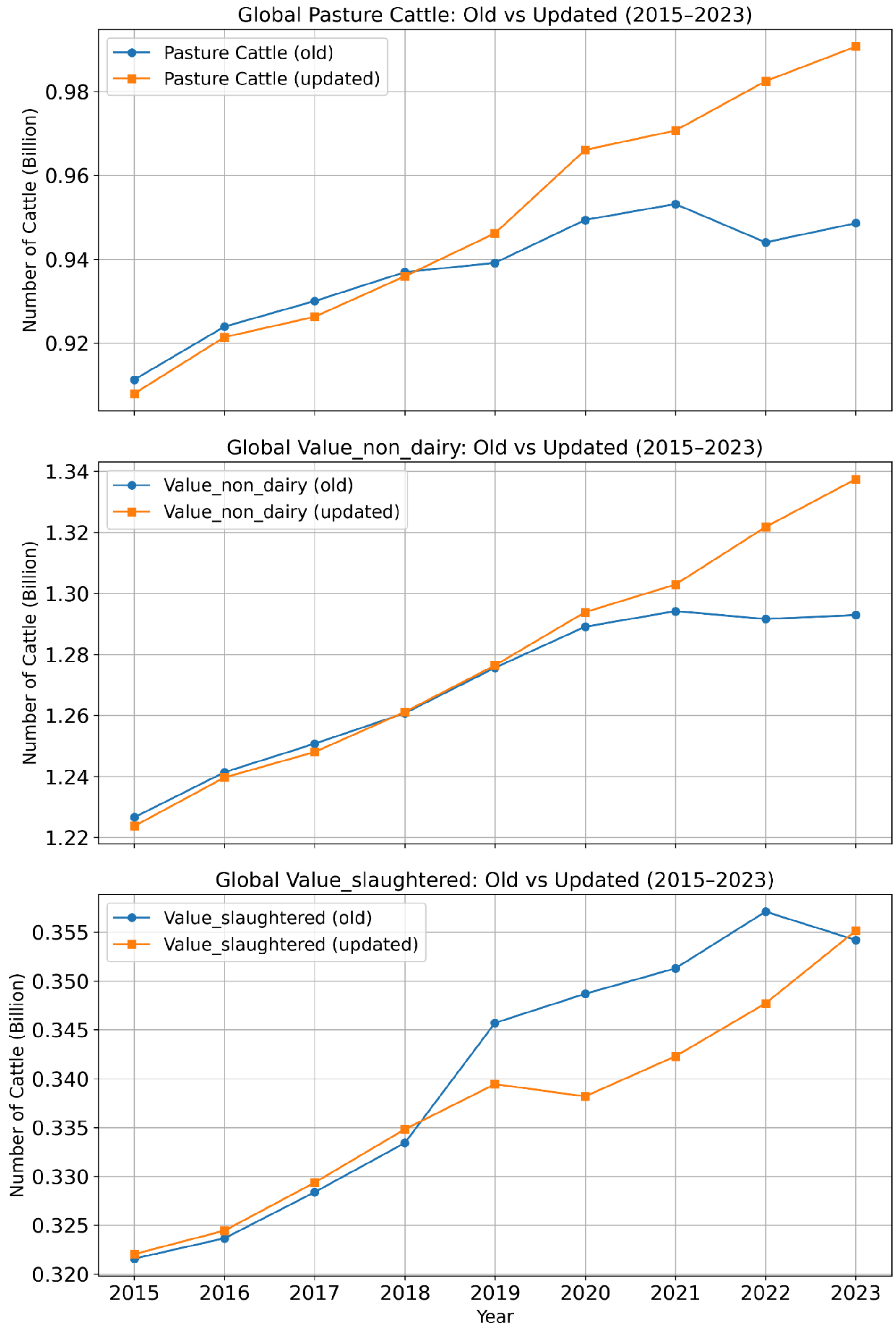


Figure 10 *Line Charts of global pasture cattle (top), non-dairy cattle (middle), and slaughtered cattle (bottom) from FAOSTAT datasets (2015-2023) used in Tier 1 (old) and Tier 2 methods (updated).*

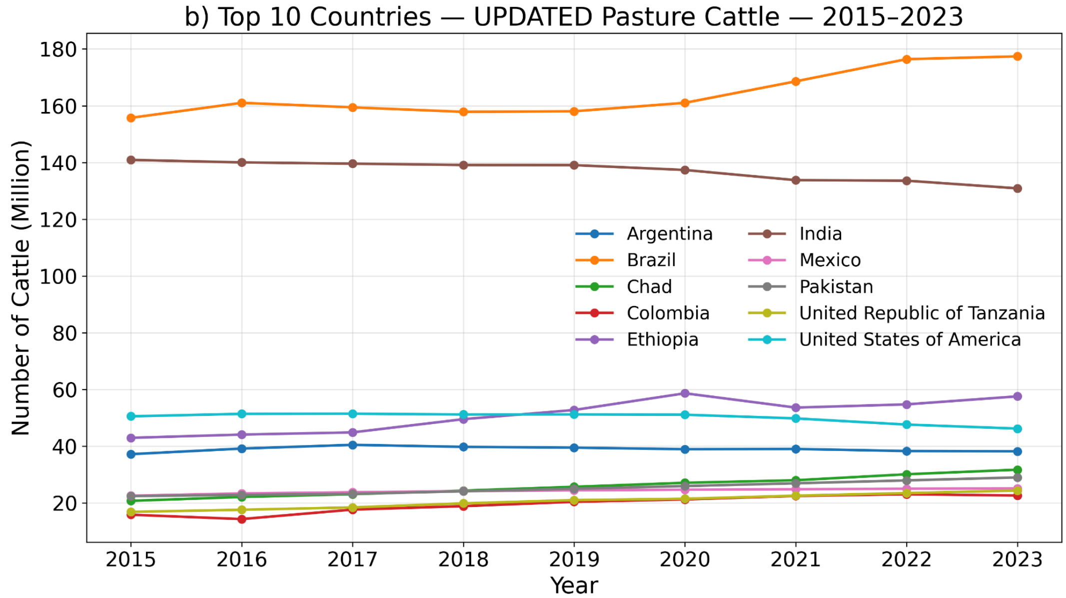


Figure 11 *Line Charts comparing pasture cattle population in the top 10 countries from FAOSTAT datasets (2015-2023) used in Tier 1 (a) and Tier 2 methods (b).*

About cattle population data used in this study, since FAOSTAT relies on various governments' data which is reported yearly, capacity factor confidence is medium. It is not considered high confidence because every country may have different systems for counting cattle. Provided by IPCC documentation, emission factors are also considered a medium-confidence source by the Climate Trace coalition. These confidence levels are critical to remember when using the data derived from the sources.

There are two main differences between results based on Tier 1 and Tier 2 (this study). One is Cattle population data and emission estimation methodology. Figure 10 showed the global differences in FAOSTAT datasets used in Tier 1 and Tier 2 methods. Across the full period, the updated dataset (data used in this study) is larger than the Tier 1 (old) for both Pasture Cattle and nondairy cattle, and lower for slaughtered cattle. Summed globally, the update adds about more than 111 million head to Pasture Cattle and more than 82 million to non-dairy Cattle, while slaughtered cattle drops ~31 million. The time-series curves show the same story year by year: from 2019 onward, the updated series pulls away—especially for Pasture Cattle—ending 2023 with a clear gap above the old line. By contrast, slaughtered cattle tracks closely until ~2018 and then the updated series consistently sits below the old one through 2023. Figure 11 and 12 showed the country-level increase/decrease in FAOSTAT datasets used in Tier 1 and Tier 2 methods. The old vs. updated comparison highlights the importance of revised livestock population datasets. Small differences in country inclusion (e.g., Sudan vs Tanzania), this shifts due to updated FAO statistics. In both datasets, Brazil and India dominate the global pasture cattle population, consistently leading across all years. Then, followed by the United States of

America, Argentina, Ethiopia. Supplementary Figure 1 top/bottom-20 bars reveal where those adjustments came from. On the increase side, large upward revisions are concentrated in countries like China, Brazil, United Republic of Tanzania, Myanmar, which drive much of the global gains in Pasture Cattle and non-dairy. On the decrease side, the biggest downward adjustments are spread across several countries (notably China (mainland) for slaughtered cattle, and countries such as Bangladesh, India, Uzbekistan, Türkiye, United States featuring among the larger negatives in other metrics). In short, the global uplift in Pasture Cattle and non-dairy primarily reflects strong positive revisions in a few large contributors, while the global decline in slaughtered values is driven by pronounced downward revisions concentrated in a smaller set of countries.

In the IPCC Tier 1 approach, enteric methane (CH_4) emissions are estimated using look-up emission factors (EFs) by region and animal category, with relay on the values (27–60 kg CH_4 per head per year) simply multiplied by head count. In contrast, Tier 2 improves this by calculating EFs from the animal's gross energy intake (GEI) and methane conversion factor (Ym) using IPCC Equations 10.16–10.21. GEI itself is derived dynamically from parameters such as body weight, mature weight, weight gain, and digestibility, allowing CH_4 EF to be computed at the individual animal level. For manure CH_4, Tier 1 applies a default country-average factor, often set at 1 kg CH_4 per head per year, implemented as a simple conversion of cattle distribution to tons. Tier 2 replaces this with a volatile-solids (VS) based model (Equations 10.23 and 10.24) that uses the maximum methane potential (B_0) and applies a methane conversion factor (MCF) weighted by climate zone and manure management system. This process converts GEI into VS and then adjusts emissions based on regional climate and storage conditions. For manure-related N_2O, the Tier 1 method applies a single global direct emission factor (EF_3 = 0.02) to all nitrogen excreted on pasture, range, and paddock, with indirect pathways estimated using uniform volatilisation and leaching factors. This approach does not account for variation in animal type, excretion rates, or environmental conditions. In contrast, the Tier 2 methodology applied here follows IPCC 2019 Chapter 11 and estimates emissions explicitly from nitrogen excretion on pasture using Equation 11.2, which multiplies the nitrogen deposited by grazing animals by the system-specific EF_3PRP. Indirect emissions are then calculated through volatilisation (Equations 11.3–11.4) and leaching/runoff (Equation 11.6) using regional parameters. This allows Tier 2 to reflect differences in animal productivity, nitrogen excretion, and environmental drivers, resulting in more spatially and temporally representative estimates of N_2O from grazing cattle than the uniform Tier 1 approach.

Figure 7 shows the global emission estimations from Tier 2 method during 2015-2024. Across 2015–2024 the Tier 2 series (built with the updated livestock inventories) track the same year-to-year shape as Tier 1 (Fig 7) (Brown et al., 2024), but is systematically higher for enteric CH_4 and manure-management N_2O, with a modest, pollutant-dependent offset for manure-management CH_4. The parallel trends indicate the underlying temporal signal is unchanged; what shifts is the magnitude, reflecting revised headcounts and herd structure in the updated dataset. The widening separation after ~2019 is consistent with upward revisions to non-dairy/pasture cattle numbers in the new data, which propagate directly into higher Tier 2 emissions, while smaller or mixed adjustments in manure CH_4 likely mirror country-specific inventory and management updates rather than a change in calculation method. Figure 12 shows the global emission estimations and top 5 countries emission estimations from Tier1 and Tier 2 methods. For the top emitters, Tier 2 generally amplifies the same leaders seen in Tier 1 (e.g., Brazil, India, the United States), and the largest Tier 2–Tier 1 gaps occur in countries where the updated inventories increased the most. In short, the national divergences map closely to the inventory revisions (size and composition of herds) and methodology differences, and these propagate up to the global totals.

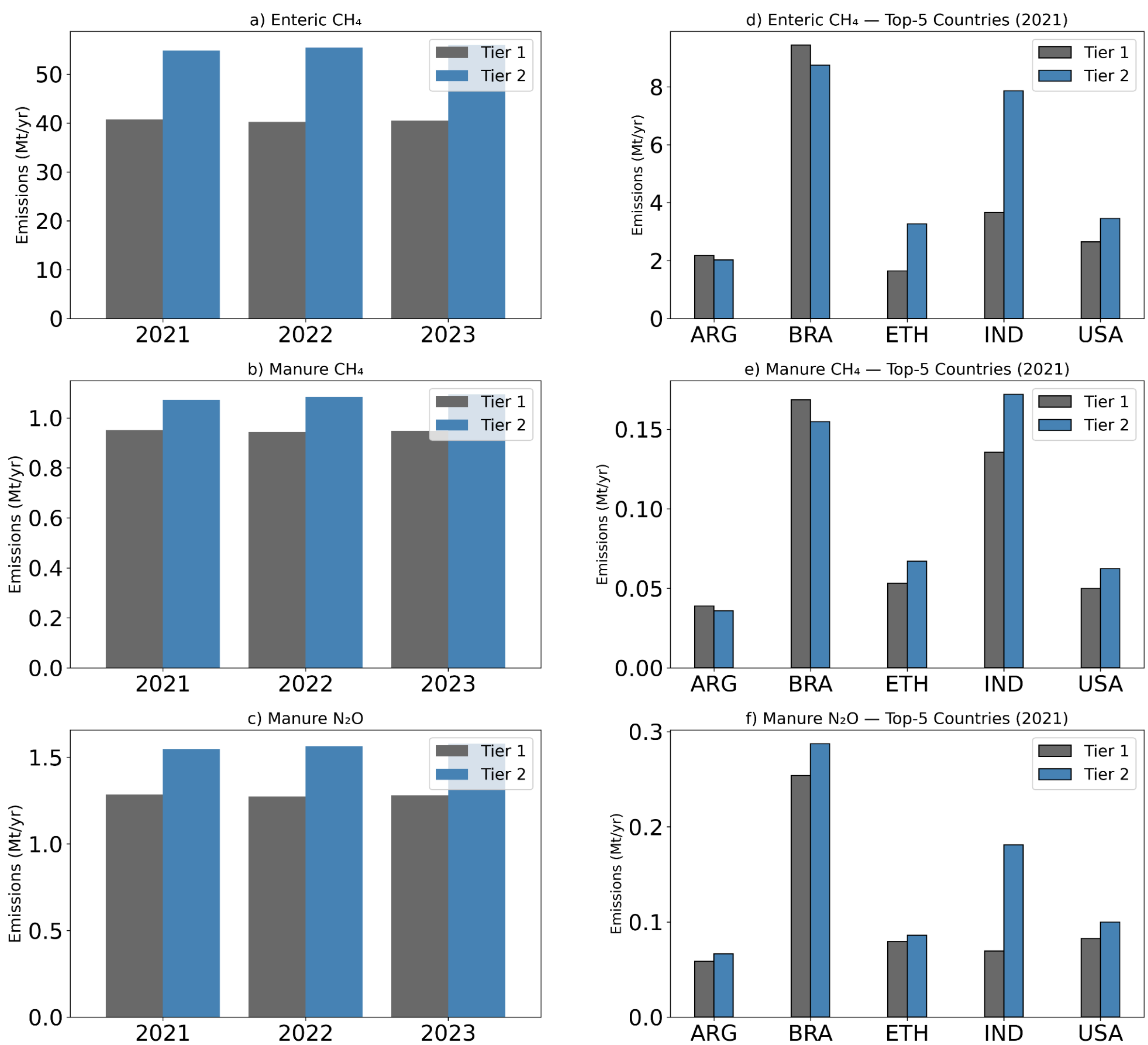


Figure 12 *Bar charts of the global total emissions (a-c) and top-5 country-level emissions (d-f) in pasture cattle based on Tier1 and Tier 2 method.*

Supplementary Figure 2 to 4 are other examples of Tier 1 and Tier 2 comparison. Supplementary Figure1 shows Global map highlighting the top 50 countries contributing to Enteric methane (CH_4) emissions. In Tier 1, emissions are dominated by Brazil (≈23%), followed by India (~9%), and then a mix of Latin American and African countries. Because Tier 1 uses fixed emission factors (kg CH_4 per head per year), the results mainly track cattle population size. This tends to overweight countries with large herds but doesn't capture productivity differences. In tier 2, Brazil remains the top emitter (~16%), but India's share increases markedly (≈14%). The U.S. (~6%) and China (~1.3%) also gain relative weight. This shift occurs because Tier 2 derives emission factors dynamically from gross energy intake (GEI) and digestibility. High-yield or intensively fed cattle (e.g., in India, the U.S., and China) show higher per-head emissions than suggested under Tier 1. Tier 1 highlights herd size; Tier 2 reveals nutritional and productivity effects, which elevate emissions in intensive systems. Supplementary Figure 2 illustrates a global map highlighting the top 50 countries contributing to Manure methane (CH_4) emissions. Similar to Enteric methane (CH_4) emissions, Brazil dominates (~18%) and India (~14%) follows, with much lower shares for other countries. This is because Tier 1 assumes a nearly constant manure CH_4 emission factor (≈1 kg CH_4 per head per year). The global distribution therefore mirrors enteric emissions. In tier 2, the map shows similar but with minor differences. Emissions increases in Europe, Russia, China, and the U.S. This is because Tier 2 models manure CH_4 from volatile solids (VS), the methane conversion factor (MCF), and climate-dependent manure management systems. Supplementary Figure 4 shows a global map highlighting the top 50 countries contributing to Manure Nitrous oxide (NO2) emissions. In Tier1, Brazil dominates (~19%), followed by India and a few Latin American countries. This happens because Tier 1 applies a single fixed emission factor (EF_3 = 0.02) for all manure systems. As a result, the distribution of manure N_2O emissions mainly mirrors cattle population size. On the other hand, in Tier2, the map shifts noticeably. Brazil remains high (~18%), but India's share rises. Tier 2 applies system-specific EF_3 values (e.g., pasture 0.005). It also adds volatilisation and leaching pathways (EF_4, EF_5).

To significantly enhance spatial resolution confidence, the most straightforward approach is to continually refresh our pastureland area datasets with more recent data sources. Unfortunately, users are unable to download complete world-scope GeoTIFF files directly from these platforms. Another potential data source is ESRI which offers a solution through its Land Cover Explorer application. The interface grants users download access to world-scope GeoTIFFs along with their associated layers. By providing more recent spatial pasture data, climate trace website visitors should expect a greater level of confidence for emission estimations.

5. Conclusion

Methane (CH_4) and nitrous oxide (N_2O) remain among the most powerful greenhouse gases, and emissions from global cattle production will continue to present major challenges for climate mitigation in the decades ahead. This study focused on advancing the monitoring and quantification of emissions from enteric fermentation and manure management in pasture-based cattle systems by comparing the IPCC Tier 1 and Tier 2 approaches.

Our analysis highlights two central differences between the approaches: (i) the use of updated livestock population inventories and (ii) the transition from static emission factors to dynamic, physiological- and climate-driven calculations. These updates result in systematically higher estimates of enteric CH_4 and manure-management N_2O under Tier 2, with global divergences after 2019 reflecting upward revisions to pasture and non-dairy cattle populations. At the national level, Tier 2 amplifies contributions from major producers such as Brazil, India, and the United States, while redistributing manure-related emissions toward regions. In short, Tier 1 largely tracks herd size, whereas Tier 2 exposes productivity, nutritional, and management effects that better reflect the heterogeneity of global cattle systems.

However, the robustness of these results is inseparable from the confidence of underlying data sources. Pastureland extent remains constrained by satellite-based estimates from 2000, carrying low confidence due to its age and lack of temporal updating. Livestock counts reported annually to FAOSTAT hold medium confidence, reflecting country-to-country inconsistencies in reporting systems. Similarly, emission factors are derived from medium-confidence sources, as they integrate assumptions about energy intake, digestibility, and manure management that vary across regions. Addressing these uncertainties, particularly through more frequent updates to global pasture datasets, will be essential to improve the spatial and temporal fidelity of emission estimates.

Since methane and nitrous oxide have such high global warming potentials, global GHG emissions from cattle are a problem that future generations will continue to wrestle with. The focus of this work is on monitoring and quantifying emissions from enteric fermentation and manure produced by cattle on pastures. With these data points on the Climate TRACE, users can use this data to analyze and consider avenues for changing systems resulting in a more sustainable ecosystem. By using the data provided by various sources, the modeling described in this paper outputs GeoTIFFs that encode emission estimates and their uncertainty values for each gas and year. Our methods present a promising avenue for analyzing the environmental impact of the cattle industry, offering a pathway toward more sustainable and responsible livestock farming practices.

Acknowledgments

6. Supplementary metadata section

In this sector, detailed descriptions of emission calculations are provided in this section. Specifically, it outlines the step-by-step procedures used to estimate CH_4 and N_2O emissions from non-dairy cattle on pasture following the IPCC 2019 Tier 2 methodology. This includes the equations, parameter sources, regional factors, and assumptions applied to compute enteric fermentation and manure management emissions.

6.1 Enteric-fermentation CH_4

Enteric-fermentation CH_4 emission was calculated using the energy balance Tier 2 approach an Enteric-fermentation CH_4 emission factor for each animal category following IPCC 2019 Equation 10.21:

$$CH^{4}_{enteric}\left(kg\ hd^{-1} yrd^{-1}\right) = \frac{GEI*Y_m}{55.65} * 365 \qquad IPCC\ Equation\ (10.21)$$

Where:
EF = emission factor, kg CH4 head-1 yr-1
GE = gross energy intake, MJ head-1 day-1
Ym = methane conversion factor, per cent of gross energy in feed converted to methane
The factor 55.65 (MJ/kg CH4) is the energy content of methane

We can measure GEI based on the Equation as shown below. Its requirement is derived based on the summed net energy requirements and the energy availability characteristics of the feed(s).

$$GEI = \frac{\left[\frac{NEm+NEa+NEl+NEwork+NEp}{REM} + \frac{NEg+NEwool}{REG}\right]}{DE} \qquad IPCC\ Equation\ (10.16)$$

Where:
NEm = net energy required by the animal for maintenance (Equation 10.3), MJ day-1
NEa = net energy for animal activity (Equations 10.4 and 10.5), MJ day-1
NEl = net energy for lactation (Equations 10.8, 10.9, and 10.10), MJ day-1
NEwork = net energy for work (Equation 10.11), MJ day-1
NEp = net energy required for pregnancy (Equation 10.13), MJ day-1
REM = ratio of net energy available in a diet for maintenance to digestible energy (Equation 10.14)
NEg = net energy needed for growth (Equations 10.6 and 10.7), MJ day-1
REG = ratio of net energy available for growth in a diet to digestible energy consumed (Equation 10.15)
NEwool = net energy required to produce a year of wool (Equation 10.12), MJ day-1
DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy, i.e. DE%/100)

Table S1 Regional parameters of Enteric-fermentation CH_4 emission for Tier 2 IPCC 2019. BW: Body weight; DE: Digestibility; Nex: Annual N excreted/head; MW: Mature weight; Ym: Fraction of GEI lost as CH_4

Region	BW (kg)	DE (%)	Nex (MJ/kg)	MW (kg)	WG (kg/day)	Ym (%)	Source (IPCC 2019)
North America	407	69	0.4	580	1.0	6.5	Annex Tables 10A.5 (BW & DE), Annex Tables 10A.4 (MW), Annex Tables 10A.3 (WG), Table Table 10.14 (Nex), plus Chapter 10 guidance for Ym
Western Europe	405	73	0.34	468	0.42	6.5	
Eastern Europe	389	66	0.36	475	0.6	6.5	
Oceania	359	60	0.33	467	0.41	6.8	
Latin America	312	67	0.34	435	0.50	7.0	
Asia	303	59	0.30	341	0.30	7.0	
Africa and Middle East	276	58	0.32	343	0.35	7.5	
Indian Subcontinent	202	55	0.27	222	0.33	7.5	
Other Europe	397	70	0.35	472	0.51	6.5	

In our Tier 2 inventory the Gross Energy Intake (GEI) equation is intentionally simplified to include maintenance (NEM), activity (NE act ≈ 10 % NEM) and growth (NEG) only, omitting net-energy terms for lactation (NEl), pregnancy (NEp), draught work (NE work) and fibre (NE wool). This is consistent with the 2019 IPCC Refinement because the herd under study is non-dairy beef cattle.

Annual enteric CH_4 emissions were calculated by multiplying the emission factors (EF, kg CH_4 $head^{-1}$ yr^{-1}) by the corresponding pasture cattle population (Activity).

6.2 Manure Management

Manure management CH_4 and N_2O emissions were estimated using the IPCC 2019 Tier 2 approach, applying region- and climate-zone-specific parameters for each cattle category.

CH_4 from Manure Management

In Tier 1, Uses a fixed CH_4 EF per region, no distinction by system or climate. Methane (CH_4) emissions from manure management were estimated following the 2019 Refinement to the IPCC Guidelines (Tier 2). Because the analysis focused exclusively on cattle maintained on pasture, we restricted the manure pathway to the pasture/range/paddock system and excluded liquid/slurry and dry systems (e.g., solid storage, dry-lot), which are not representative of pasture-based management. The annual CH_4 emission factor for manure management was calculated using IPCC 2019 Equation 10.23:

$$EFCH4 = VS * Bo * MCF * 0.67 * \frac{365}{100} \quad IPCC\ Equation\ (10.23)$$

Where:
$EF_{(CH_4)}$ = CH_4 emission factor, kg CH_4 head^{-1} yr^{-1}
VS = volatile solids excretion, kg head^{-1} day^{-1} (calculated using IPCC Equation 10.22 based on gross energy intake, digestibility, and ash content)
B_0 = maximum CH_4-producing capacity of manure, m^3 CH_4 kg^{-1} VS
MCF = methane conversion factor for the manure management system, % (adjusted for region-specific climate and system type)
0.67 = conversion factor from m^3 CH_4 to kg CH_4

Volatile solids (VS) were calculated from feed intake, digestibility, and ash content using the IPCC 2019 refinement equation:

$$VS = \left[GEI * \left(1 - \frac{DE}{100}\right) * \left(1 - \frac{Ash}{100}\right)\right] * 0.45 \quad Equation\ (10.24)$$

Where:
GEI = gross energy intake (MJ head^{-1} day^{-1})
DE = digestibility of feed (%)
Ash = ash content of manure (%).
Climate zones were assigned using the dominant mode from 2015–2024 monthly temperature rasters, and the corresponding default MCF values for pasture/range/paddock were applied. Because manure is excreted and decomposes directly on pasture, the overall methane potential is considerably lower than in confined systems.

N_2O from Manure Management

We estimated N_2O emissions from urine and dung deposited by grazing cattle on pasture using the Tier-2 formulation in the 2019 Refinement (Chapter 11), restricting activity data to the pasture/range/paddock pathway. Nitrogen (N) deposited on pasture by grazing cattle (FPRP, kg N yr^{-1}) was computed as:

$$F_{PRP} = \Sigma\,[\,N(T) \times Nex(T) \times MS(T, PRP)]\ \ IPCC\ Equation\ (11.5)$$

Where:
N(T): cattle headcount,
Nex: annual N excretion rate (kg N head^{-1} yr^{-1})
MS: the fraction of excreted N deposited on pasture

Direct N_2O-N from grazing deposition was:

$$N2O - N_{Direct} = F_{PRP} \times EF3PRP \quad IPCC\ Equation\ (11.5)$$

$$N2O\_Direct \ = N2O - N\_Direct \times (44/28)\ \ IPCC\ Equation\ (11.5)$$

Where:

EF3PRP (cattle) default =0.004 kg N_2O-N per kg N deposited (0.4%) (Table 11.11)

44/28: Conversion factor from N_2O-N to N_2O (molecular weight ratio of N_2O to N_2)

Indirect N_2O emissions via volatilization and leaching/runoff were estimated using IPCC Equations 11.10, Equations 11.11, Table 11.3 and Table 11.11, applying system-specific emission factors (EF_4, EF_5) and fractions of nitrogen lost via volatilization (FracGASM) and leaching (FracLEACH).

$$N2O - N_{ATD} = F_{PRP} \times FracGASM \times EF4 \times \left(\frac{44}{28}\right) \; IPCC\ Equation\ (11.11)$$

$$N2O - N_{L} = \left(F_{PRP} \times FracLEACH - H\right) \times EF5 \times \left(\frac{44}{28}\right) \; IPCC\ Equation\ (11.10)$$

Where:

FracGASM= 0.21 (fraction of excreta N volatilized)

EF4= (N_2O-N per volatilized N) aggregated default=0.010

FracLEACH−(H)=0.24

EF5=0.011 kg N_2O-N per kg N leached/runoff

44/28=Conversion factor from N_2O-N to N_2O (molecular weight ratio of N_2O to N_2)

In our Tier 2 inventory, manure management system allocations, MCFs, and N_2O emission factors were applied at the region × climate zone × pasture cattle. System shares were determined from region-specific datasets, and climate assignments were derived from multi-year (2015–2024) dominant climate raster layers. This approach enables both pixel-level spatial mapping (GeoTIFF) and country-level aggregation (CSV tables) for CH_4 and N_2O manure management emissions.

Additionally, data is in the form of GeoTIFF files following EPSG 4326 standards (WGS84, 2004). These files cover GHG emissions from manure and enteric fermentation on pastureland, including global warming potentials from 2015 to 2022. The data also gauges the uncertainty in emissions, emission factor, capacity, and capacity factor for both GHGs in these sectors.

Table S2 General dataset information for pastures.

General Description	Definition
Sector definition	Enteric fermentation for cattle on pasture and cattle manure on pasture
Temporal Coverage	2015 – 2024
Temporal Resolution	Annual (original); Monthly (on website, see Temporal Disaggregation of Emissions Data for the Climate TRACE Inventory)
Data format(s)	GeoTIFF
Coordinate Reference System	EPSG:4326, decimal degrees
Total emissions for 2024	2,015,595,255 tonnes CO2e GWP100
Ownership	We used permit data and research to identify ownership information
What emission factors were used?	IPCC tier 2

What is the difference between a "NULL / none / nan" versus "0" 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 CO2e GWPs. CO2e conversion guidelines are here:https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf

Table S3 Source level metadata description confidence and uncertainty for reservoirs.

Data attribute	Confidence Definition	Uncertainty Definition
type	Not used; N/A	Not used; N/A
capacity_description	Low: the pastureland capacity data is 23-year-old data	Capacity uncertainty is the variance of the neighboring grid cells.
capacity_factor_description	Medium: every country may have different systems for counting cattle	Cow count uncertainty estimates, expressed as a percentage above or below the mean estimate (i.e., +/-XX%)
capacity_factor_units	Pasture percent area within each grid cell	Not used; N/A
activity_description	Number of cattle distributed on pasture	Not used; N/A
CO2_emissions_factor	Not used; N/A	Not used; N/A
CH4_emissions_factor	Medium: based on IPCC region-specific parameter uncertainty	IPCC uncertainty estimates, expressed as a percentage above or below the mean estimate (i.e., +/-XX%)
N2O_emissions_factor	Medium: based on IPCC emissions factors	IPCC uncertainty estimates, expressed as a percentage above or below the mean estimate (i.e., +/-XX%)
other_gas_emissions_factor	Not used; N/A	Not used; N/A
CO2_emissions	Not used; N/A	Not used; N/A
CH4_emissions	Medium: based on IPCC region-specific parameter uncertainty	Given as an interval with an lower and upper bound of value
N2O_emissions	Medium: based on IPCC emissions factors	Given as an interval with an lower and upper bound of value
other_gas_emissions	Not used; N/A	Not used; N/A
total_CO2e_100yrGWP	Medium: based on IPCC emissions factors	Given as an interval with an lower and upper bound of value
total_CO2e_20yrGWP	Medium: based on IPCC emissions factors	Given as an interval with an lower and upper bound of value

Data citation format:

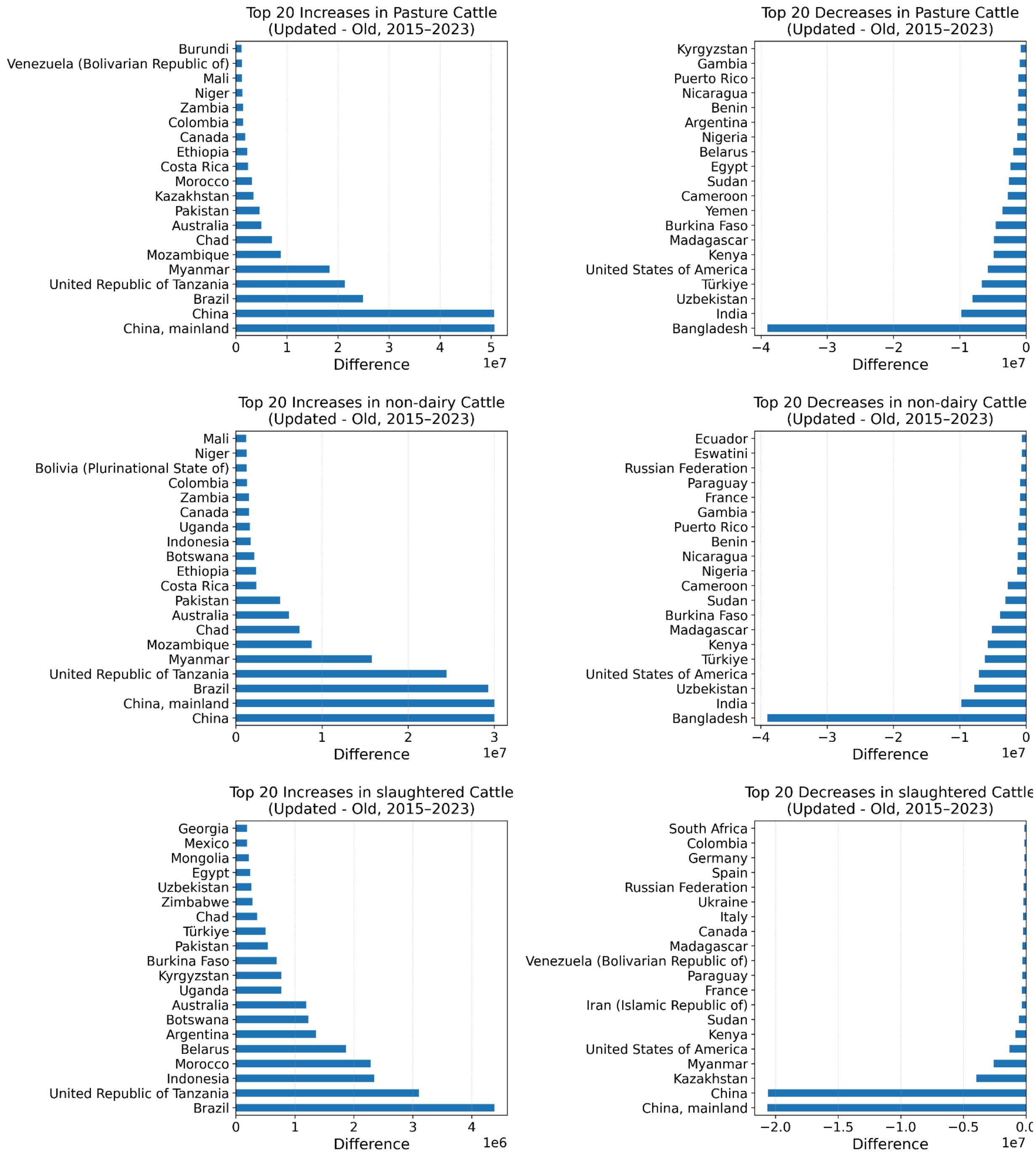
Alifu, H., Sagan, V. Tesser, D., Davitt, A., Sridhar, L., and Betz, L. (2025) *Agriculture sector-Cattle Emissions from Enteric Fermentation and Manure Left on Pasture.* WattTime and The Saint Louis University Remote Sensing Laboratory (SLU/RSL), USA, Climate TRACE Emissions Inventory. https://climatetrace.org [Accessed date]

Geographic boundaries and names: 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:

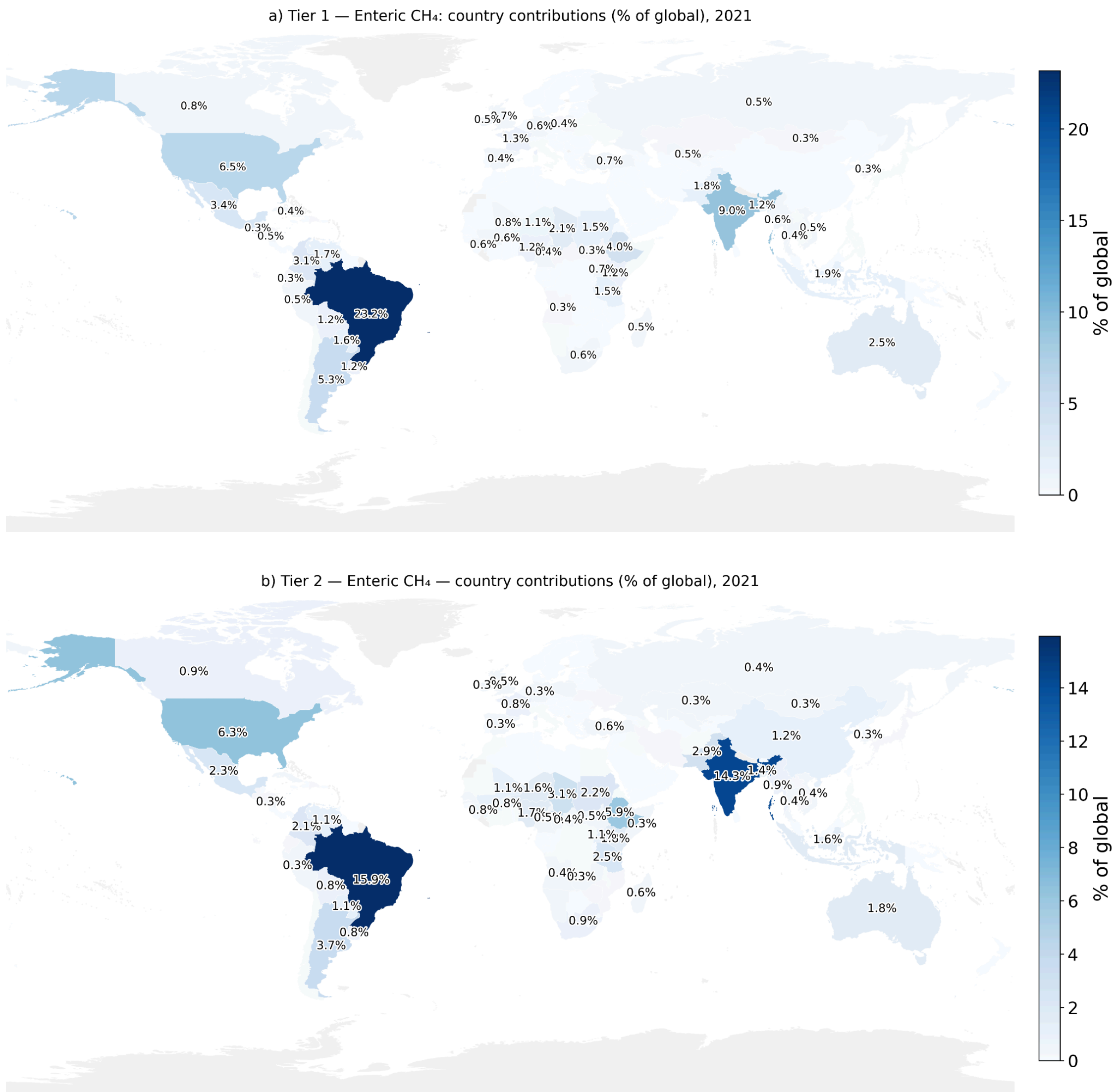
- HKG (China, Hong Kong Special Administrative Region) and MAC (China, Macao Special Administrative Region) are reported at GADM level 0 (country/national);
- Kosovo has been assigned the ISO3 code 'XKX';
- XCA (Caspian Sea) has been removed from GADM level 0 and the area assigned to countries based 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.

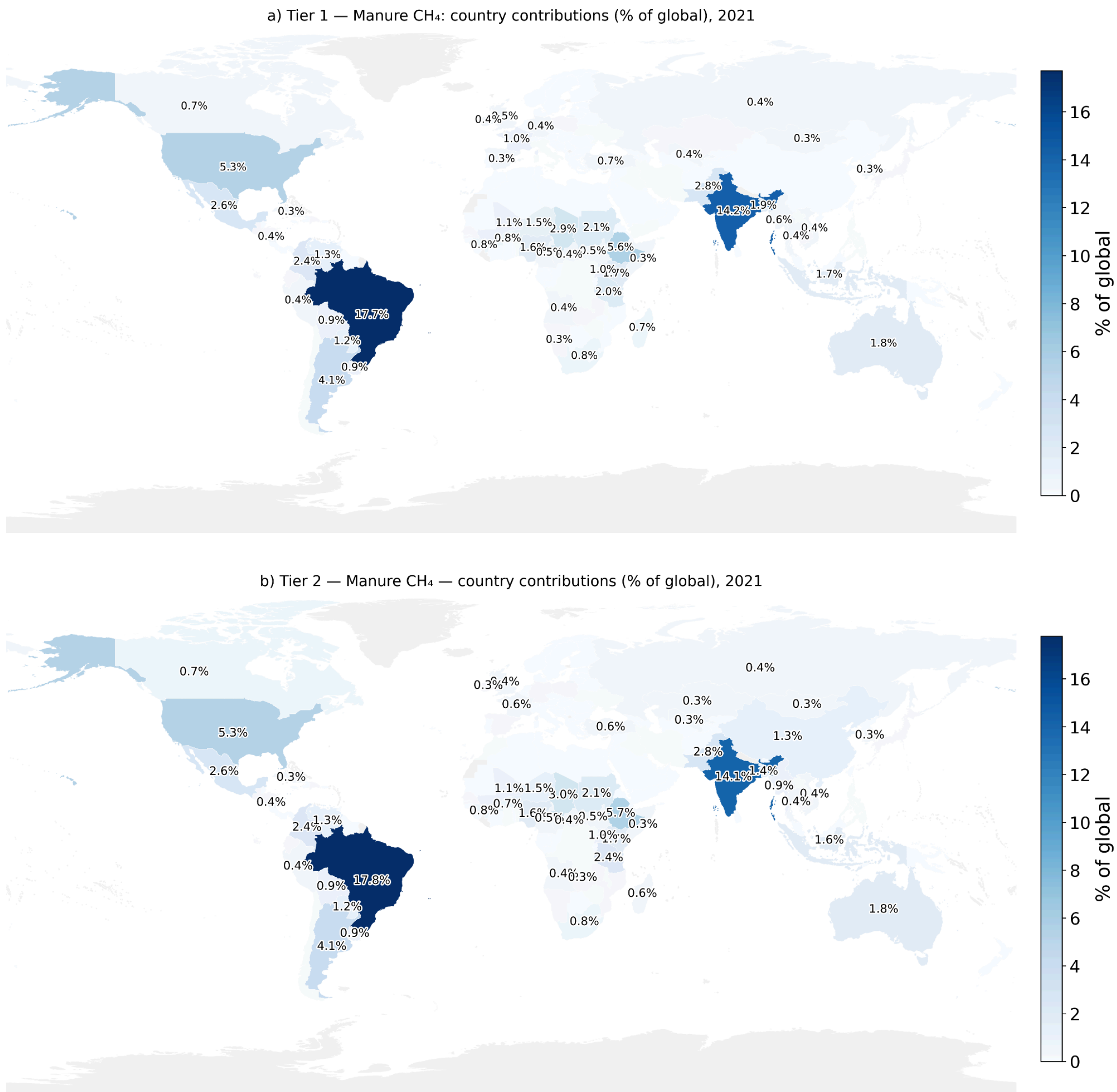
Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify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



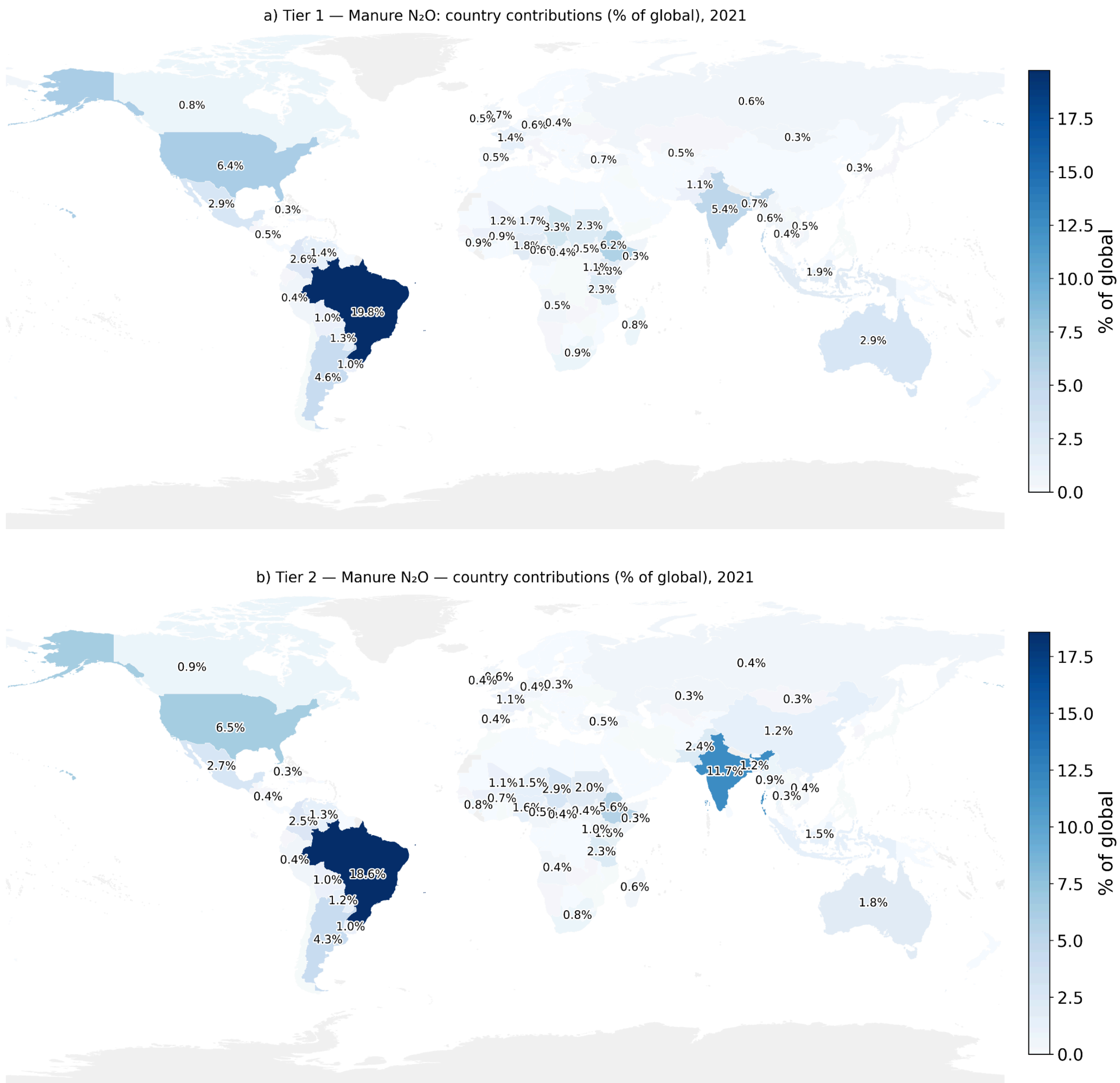
Supplementary Figure 1. *Bar charts of the top-20 country-level increases and decreases in pasture cattle, non-dairy cattle, and slaughtered cattle from FAOSTAT, 2015–2023. Values show Updated (Tier 2) − Old (Tier 1); positive bars indicate upward revisions, and negative bars indicate downward revisions.*



Supplementary Figure 2. *Global map highlighting the top 50 countries contributing to methane (CH_4) emissions Enteric Fermentation.*



Supplementary Figure 3. *Global map highlighting the top 50 countries contributing to methane (CH_4) emissions from Manure Management.*



Supplementary Figure 4. *Global map highlights the top 50 countries contributing to Nitrous oxide (NO2) emissions from Manure Management.*

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