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, 2006). Appropriately monitoring and quantifying these emission sources is of paramount importance in managing and mitigating the environmental impacts of livestock farming. 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 (US Environmental Protection Agency, 2023). However, nitrous oxide from manure on pasture is about 300 times more potent than CO_2 .

Current methods in reporting cattle pasture emissions include FAOSTAT estimation by using IPCC emission factors (FAO, 2022). They estimated enteric fermentation and manure management emissions from cattle 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 an ML model on Sentinel-2 satellite imagery and biomass measurement data (Chen, 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.

Since its official standardization in 2019, GeoTIFFs - georeferenced raster images - have been a useful tool in capturing spatially defined emissions data (Open Geospatial Consortium, 2023). With the developments of high-resolution mapping and geospatial analysis, this format offers a comprehensive view of emissions sources in pasturelands, providing crucial insights that can improve emissions management strategies. This paper describes the methodology and relevance of generating GeoTIFFs for emissions from enteric fermentation and cattle manure left on pastures.

2. Materials and Methods

We utilized pandas, geopandas, and the rasterio library to create the GeoTIFFs and organize the data from various sources. Calculations of methane and nitrous oxide emissions from enteric fermentation and manure left on pasture are described by the IPCC in chapters 10 and 11 which we share below (Dong et al., 2006; De Klein et al., 2006).

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. 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 three data sources. These three were the following: Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), Global Administrative Areas (GADM), and NASA Socioeconomic Data and Applications Center (SEDAC). 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. For slaughtered cattle, data is available for the years 2015-2022. For non-dairy cattle, data is available for the years 2015-2021, with years 2022 and 2023 generated using a 2-year rolling average. However, since the slaughtered cattle data included the year 2022, we only generated the year 2023 using a rolling average.

Next, we used NASA SEDAC pasture data which provides a pastureland area percentage for each .1 x .1 degree square (~10km at the equator) represented as GeoTIFF pixels in the world for the year 2000. This data was obtained by applying machine learning to satellite imagery to determine the type of land area in each square (Ramankutty, 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.

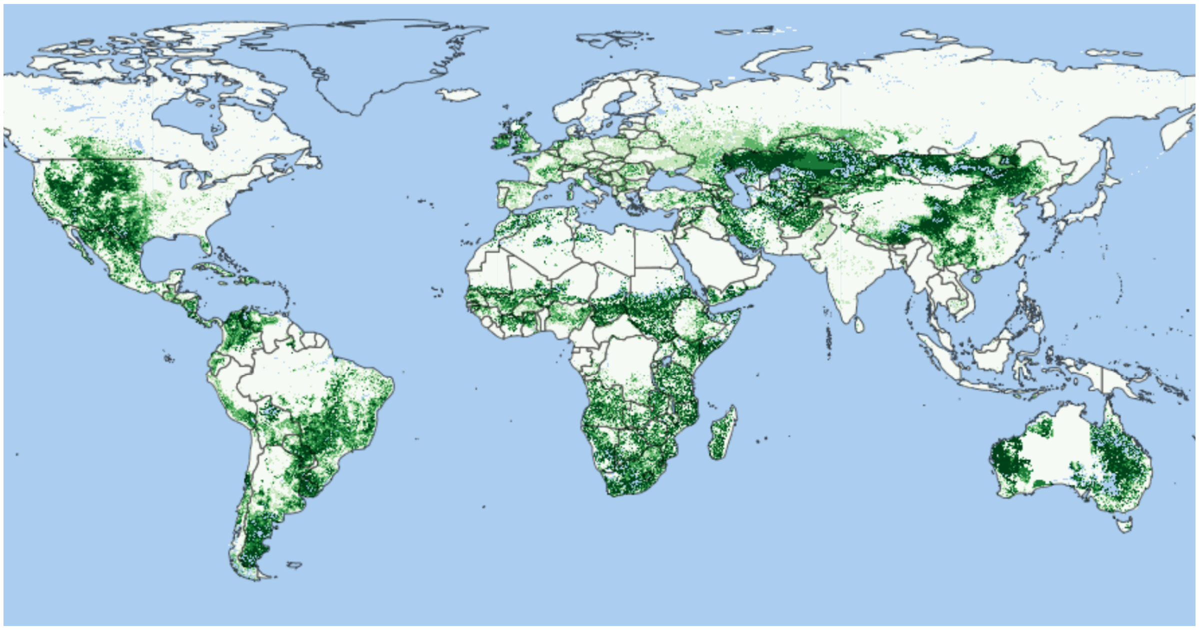


Figure 1 *NASA SEDAC Pasture data for the year 2000.*

2.2 Methods

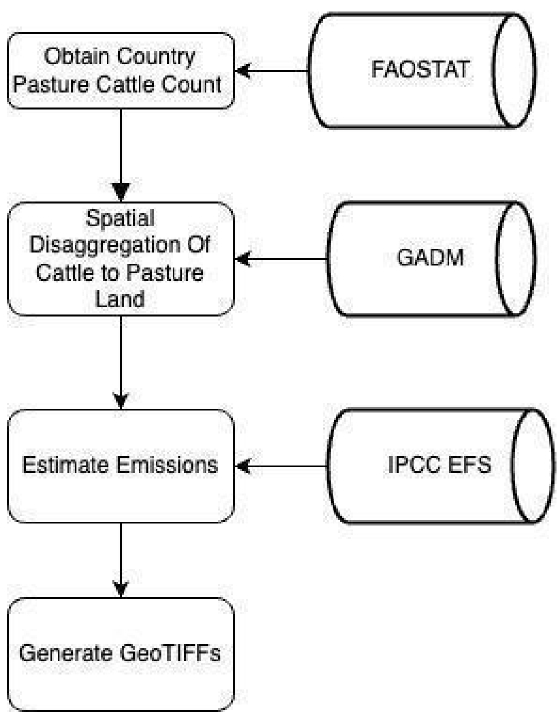


Figure 2 *Methodology Flowchart to estimate emissions from cattle on pasture*

Our primary goal was to create 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. Additionally, GeoTIFFs were created to show the uncertainty for each sector and gas for emissions, emission factor, capacity, and capacity factor.

2.2.1 Cattle Disaggregation

For obtaining any emissions arising from cattle, 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.

1. The first step was to obtain the total number of cattle in the pasture area by subtracting the count of slaughtered cattle from the total non-dairy cattle 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. This could be due to their cattle and their slaughtered cattle all living in pasture areas (Bourn, 2003). The list of countries resulting in negative values is discussed further and provided in Table S1 of the Climate TRACE methodology, "*Country-level Enteric Fermentation and Manure Management Emissions Estimates from Cattle Operations*".

2. Using SEDAC pasture area percentage for each .1 x .1 degree polygon, we obtained the world grid of polygons with their respective pasture cover percentage as a pandas dataframe.

3. Next, 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.

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 factor.
      $$polygon_{factor} = polygon_{pasture\_area} / total^{c}_{area}$$

5. Then multiply the SEDAC polygon's factor by its country's total assets to obtain the total number of cows in the pixel.
   $$polygon_{assets} = polygon_{factor} * country_{assets}$$

Now that we have the spatially distributed pasture cattle, emission factors were applied using IPCC 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). The output, which captures the estimated amount of cattle within each .1 x .1 degree square, was used as an input to the following GHG emissions calculations from both enteric fermentation and manure management.

Table 1 *IPCC Regional Emission Factors for Enteric Fermentation from Table 10.11.*

Region	Regional Emission Factors
North America	53
Western Europe	57
Eastern Europe	58
Oceania	60
Latin America	56
Asia	47
Africa and Middle East	31
Indian Subcontinent	27

The first subsector to calculate emissions was enteric fermentation, where the methane emissions were calculated using the following equation 10.19 from IPCC: $E_{CH4} = (EF/1000) * N$ where N is the number of cows, EF is the regional emissions factor, and E_{CH4} is the methane released in tonnes per year. The regional emission factors can be found in Table 1 (Dong et al., 2006).

Manure Management

The second subsector to estimate emissions was manure management, which emits both methane and nitrous oxide. For CH_4, the IPCC estimates that each cow manure emits 1kg of CH_4 per year (Rivera, 2021). Therefore, the number of cattle was divided by 1,000 to obtain CH_4 per year to convert kilograms to tonnes. For N_2O, the estimates were derived from both direct emissions of cow manure and indirect emissions from runoff. As with methane, these calculations were derived from IPCC documentation (De Klein et al., 2006). For each pixel region, the following steps were taken to estimate direct N_2O-N from cattle:

1. The nitrogen deposit rate (N_rate) was mapped to each country and the average cattle mass for that country is shown in Table 2.

Table 2 *Regional Nitrogen Rate and Average Mass for each region.*

Region	N_rate	average_mass
North America	.31	389
Western Europe	.33	420
Eastern Europe	.35	391
Oceania	.5	330
Latin America	.36	305
Africa and Middle East	.63	173
Asia	.34	317

2. The annual N excretion per cow was obtained for that country using the following equation from equation 10.30 in Chapter 10 of the IPCC documentation:
$$annual\_N = N\_rate * (average\_mass/1000) * 360.$$

3. The N deposited is calculated by multiplying the annual N per cow by the number of cows in that pixel region. Finally, the nitrogen deposited is multiplied by the emission factor of .02 to estimate the direct N_2O-N emissions per year for that pixel region:

$$N2O - N_{direct} = annual_N * cattle * 0.02$$

For the indirect N_2O-N emissions, the emissions were summed for N volatilized and runoff. The equation is as follows:

$$N2O - N\_indirect = annual\_N * (EF\_volatized + EF\_runoff)$$

where EF_volatized is .02 and EF_runoff is 0.00225. As a last step, the indirect and direct were summed and multiplied by 44/28 to total N_2O emissions:

$$Total\ N2O = \frac{44}{28} * (N2O - N_{indirect} + N2O - N_{direct})$$

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 gasses 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:

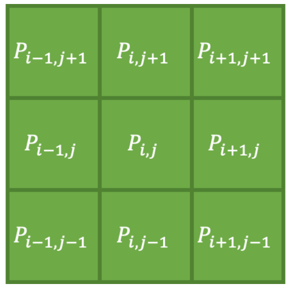
$$GWP\ 20\ year = CH4\ Emissions * (80.8 \pm 25.8) + N2O\ Emissions * (273 \pm 118)$$

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 50% uncertainty and the capacity factor has a 20% according to the IPCC (Dong, 2006). To obtain the capacity 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

3. Results

We provide GeoTIFFs for pasture cattle distribution, uncertainties, and emission estimates for enteric fermentation and manure management. Figures 4 through 6 are examples of the GeoTIFFs for 2022 GHG emission estimates with the countries outlined in red.

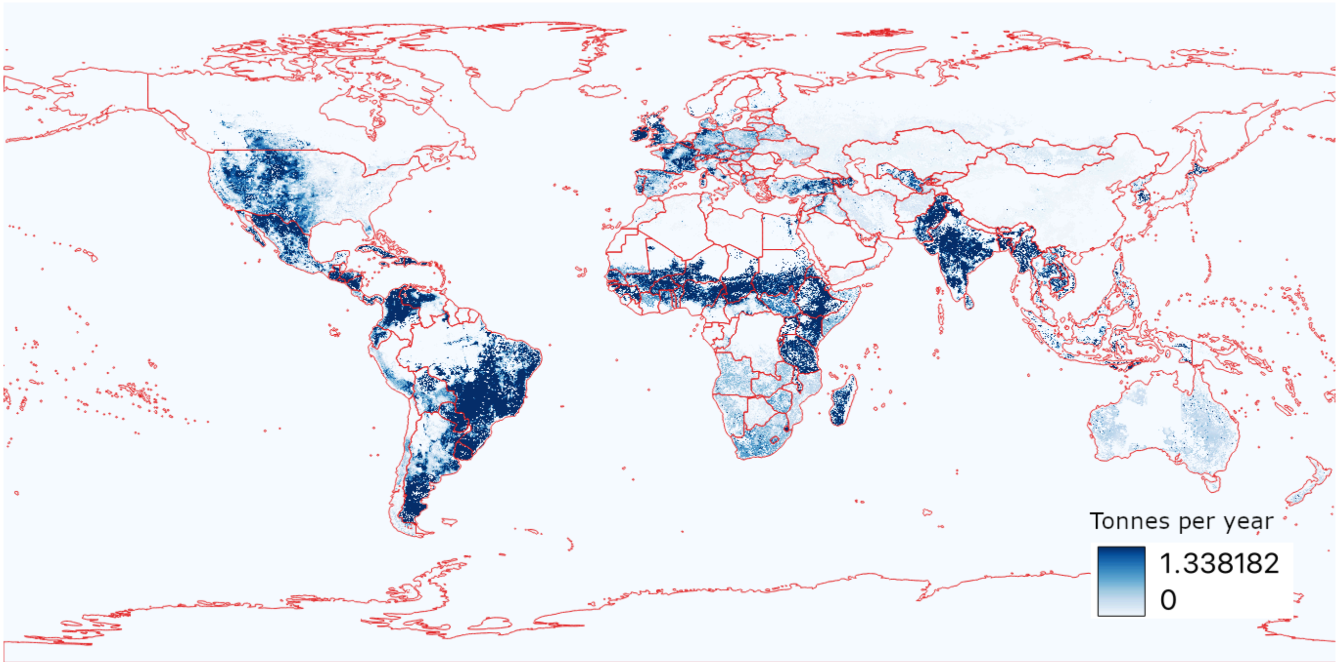


Figure 4 *Manure Management CH_4 Estimates 2022.*

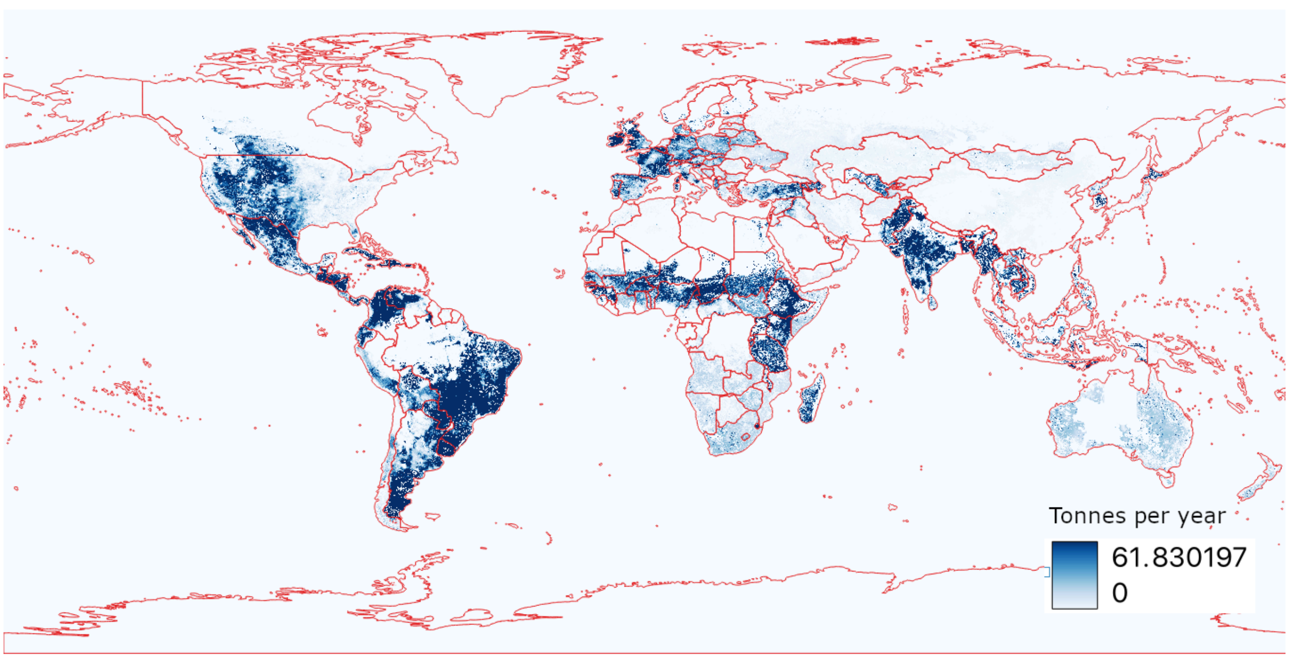


Figure 5 *Enteric Fermentation CH_4 2022.*

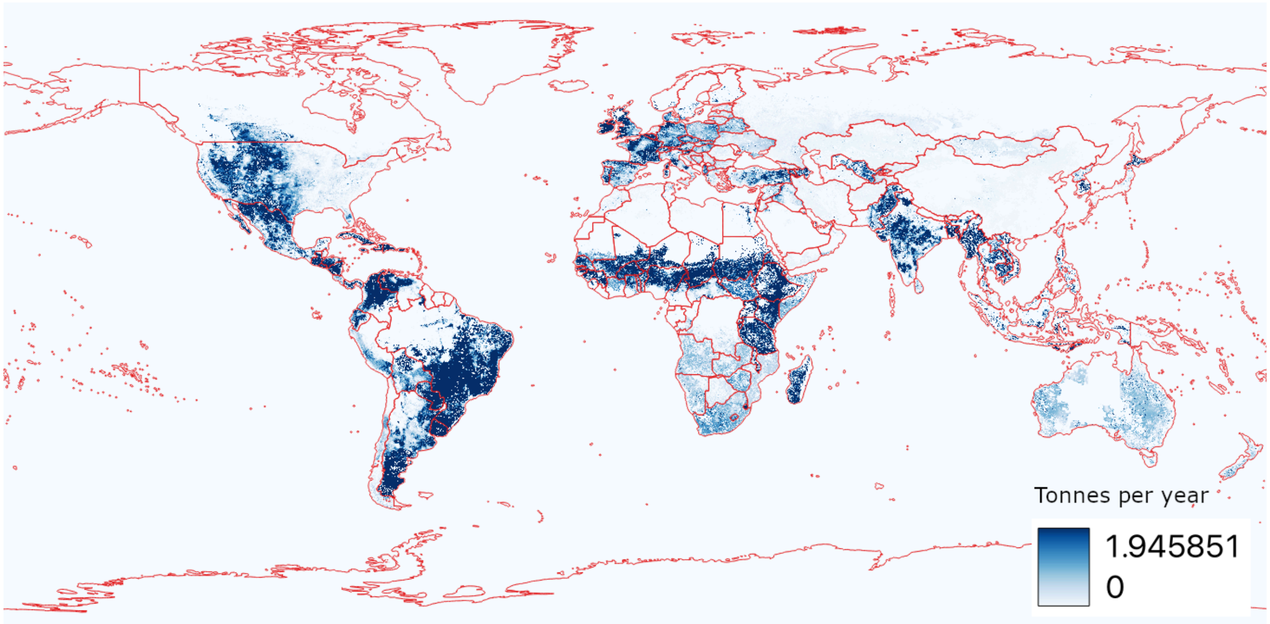


Figure 6 *Manure Management N_2O 2022.*

Figure 7 displays the time series of the global sum of emissions for each GHG by year. There has been a steady increase in emissions from this sector since 2015 with an anomalous maximum in 2020 because of the increasing cattle populations globally.

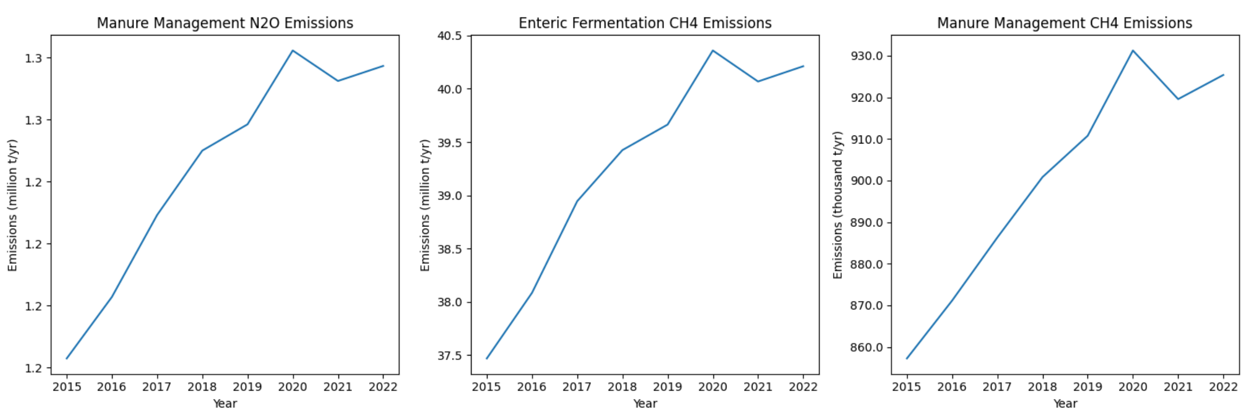


Figure 7 *Line Charts of Global Emission Estimates. Left graph, manure management N2O emissions; Center graph, enteric fermentation CH_4 emissions; Right graph, manure management CH_4 emissions.*

As shown in Figure 8, the top 5 countries with the most cows are the following in descending order: Brazil, India, Ethiopia, USA, and Argentina.

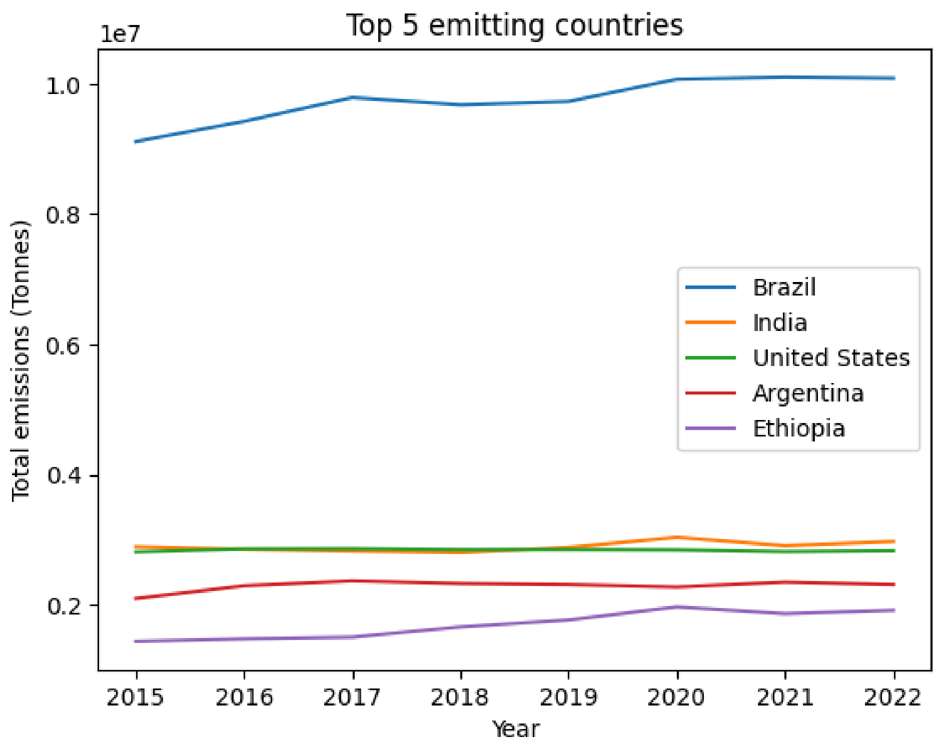


Figure 8 *Line Charts of Top 5 Emitting Countries - Brazil, India, U.S., Argentina, and Ethiopia.*

4. Discussion

When considering the data for calculating pastureland emissions, it is important to consider the confidence of their sources. First, the pastureland capacity data does not change in the years we generated because it is generated from satellite data in the year 2000. This 23-year-old data source was labeled with low confidence. 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 from a medium-confidence source by the Climate Trace coalition. These confidence levels are critical to remember when using the data derived from the sources.

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

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
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6. Supplementary metadata section

In the sector, 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 S1 General dataset information for pastures**.**

General Description	Definition
Sector definition	*Enteric fermentation for cattle on pasture and cattle manure on pasture*
Temporal Coverage	*2015 – 2023*
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 2023	*126,016,340 tonnes CO_2e*
Ownership	*We used permit data and research to identify ownership information*
What emission factors were used?	*IPCC tier 1*
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 CO_2e GWPs. CO_2e conversion guidelines are here:https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf

Table S2 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*: It is not considered high confidence because 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	Not used; N/A	Not used; N/A
activity_description	Not used; N/A	Not used; N/A
CO2_emissions_factor	Not used; N/A	Not used; N/A
CH4_emissions_factor	*Medium*: based on IPCC emissions factors	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 emissions factors	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: Brown, N., Jimenez, D., Davitt, A., Reilly, E. (2024) *Agriculture sector-Cattle Emissions from Enteric Fermentation and Manure Left on Pasture.* WattTime and The Johns Hopkins University Applied Physics Laboratory (JHU/APL), 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.

References

1. Bourn, D., (2003) *Livestock Dynamics in the Arabian Peninsula - University of Oxford*. Available at: https://ergodd.zoo.ox.ac.uk/download/reports/Livestock%20Dynamics%20in%20the%20Arabian%20Peninsula.pdf (Accessed: 20 October 2023).
2. Chen, Y., Guerschman, J., Shendryk, Y., Henry, D. and Harrison, M.T., 2021. Estimating pasture biomass using sentinel-2 imagery and machine learning. Remote Sensing, 13(4), p.603.
3. Dong, H., McAllister, T. and Mangino, J. (2006) *Chapter 10 IPCC GUIDELINES FOR EMISSIONS FROM LIVESTOCK AND MANURE MANAGEMENT*. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf (Accessed: 11 October 2023).
4. De Klein, C., Novoa, R. and Ogle, S. (2006) *Chapter 11 IPCC GUIDELINES FOR EMISSIONS N2O EMISSIONS FROM MANAGED SOILS, AND CO2 EMISSIONS FROM LIME AND UREA APPLICATION*. Available at:

https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf (Accessed: 11 October 2023).

5. FAO. (2022). FAOSTAT Climate Change, Emissions, Manure Management. [Online] Available at: http://www.fao.org/faostat/en/#data/GM (Accessed 27 October 2023]).
6. Chapter, I.P.C.C., 2006a. 10: Emissions from livestock and manure management. *Agriculture, Forestry and Other Land Use.* Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf
7. Chapter, I.P.C.C., 2006b. 11: N2O Emissions from Managed Soils, and CO2 Emissions from Lime and Urea Application. *Agriculture, Forestry and Other Land Use.* Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf
8. *Nga geomatics - WGS 84* (2004) *NGA Geomatics - WGS 84*. Available at: https://earth-info.nga.mil/index.php?dir=wgs84&action=wgs84 (Accessed: 11 October 2023).
9. Open Geospatial Consortium. (2023). OGC GeoTIFF Standard. Available at: https://www.ogc.org/standard/geotiff/ (Accessed: 1 November 2023).
10. Ramankutty, N., Evan, A.T., Monfreda, C. and Foley, J.A., 2010. Global agricultural lands: Croplands, 2000. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY (accessed 5 January 2019). DOI, 10, p.H4C8276G10.
11. Rivera, J.E. and Chará, J., (2021) CH4 and N2O emissions from cattle excreta: a review of main drivers and mitigation strategies in grazing systems. Frontiers in Sustainable Food Systems, 5, p.657936.
12. US Environmental Protection Agency. (2023) Understanding Global Warming Potentials. [Online] Available at: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (Accessed 2023-08-04])