The Nature Conservancy

Livestock Inventory: Final Results for CONUS

Prepared by:

The team at Regrow Ag., Inc

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Executive Summary & Research Objective

This report is designed to be consumed in conjunction with the TNC Livestock Inventory workbook

Livestock contributes to roughly 14.5% of global greenhouse gas emissions, representing a total of 7.1 gigatons of CO_2 equivalent (CO_2 eq) emissions every year[1]. In the United States, livestock is responsible for 36% of all anthropogenic methane (CH_4) emissions, and yet it remains difficult to accurately quantify the livestock emissions on sub-national to farm scales due to the variability in the size, type, and management practices of animal operations, and the limited and/or inconsistent capture of those datapoints.

The question for this research report was: how can we further refine enteric and manure emission factors at a state level in the United States? The ability to perform these assessments at scales of interest enables more accurate baselining of emissions and allows companies and organizations to identify patterns of risk and opportunity related to emissions mitigation that would not have been identified with reliance on only national values. This also disentangles the individual variables from the whole, which allows emissions to be updated more minutely and incrementally.

Project Objectives:

- Using a bottom-up approach, quantify livestock emissions for dairy and beef cattle in CONUS at the state level.
- Develop an interactive state-level inventory and maps of enteric and manure emissions for livestock.
- Compare project-derived emissions against existing inventories from EPA.
- Evaluate inventory approach and offer recommendations for next steps.

Key Insights:

- In order to establish comprehensive and standardized processes to calculate emissions, we prioritized data sources that contained both the depth and breadth of inputs we were looking for, aggregated at a state level.
- Sourcing, transcribing, and standardizing data represents a significant body of work in the creation of a livestock inventory.
- ManureDNDC's updated dairy-specific enteric equation, which was used for simulating enteric emissions within this project, generated results that are largely in line with EPA estimates, though generally with lower variability.

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[1] https://www.fao.org/news/story/en/item/197623/icode/

- Dairy manure emissions are more variable state to state than the beef manure emissions, largely due to common manure management practices in beef operations.
- Emissions vary by state and system, related primarily to forage intake, manure management system, and climate.

Methodology

Target Inputs

We addressed this broader challenge of a state-level inventory by first determining the data inputs that are the most significant drivers of enteric and manure emissions across dairy and livestock operations. This enabled us to focus our research on obtaining only the inputs that we understand to be key components of overall emissions and/or emission variability within a specific animal-type category (cattle). Table 1 documents the target inputs for this preliminary inventory.

Table 1. High level overview of key data inputs required for both enteric and manure based emissions

Enteric Inputs	Manure Inputs
• Number of head • Animal class/type (age) Dairy • Neutral Detergent Fiber (NDF) • Dry matter intake (DMI) Beef • Gross Energy Intake (GEI) • Methane conversion rate (Ym)	• Number of head • Animal class/type • methane conversion factor (MCF) by management type • % manure by management type, waste management system (WMS) • Volatile solids (VS) • Max CH4 potential (B_o) • Average annual temperature

Data Availability and Inputs

Once the target inputs were identified, we were able to commence our data collection process. Within this part of our research, we had two objectives: capture raw data that can be used to inform and refine state-level enteric and manure emissions, and evaluate the availability, standardization, strengths, and limitations of the sources of this raw data.
We used two primary sources of data for this project - EPA and IFEEDER.

EPA

We relied heavily on the EPA livestock inventory throughout this inventory creation, utilizing animal numbers, animal characteristics, management system data and equations from the 2020 EPA report. These values and equations are detailed throughout the spreadsheet and report. This source was especially valuable because the data was broken into the aggregation level specified in the scope of work (e.g. state level) and it was standardized for all data points. To date, we were unable to find this data in a format that allowed for simple parsing, so all data from the EPA was manually transcribed into the inventory spreadsheet.

IFEEDER

We utilized the Institute for Feed Education and Research (IFEEDER) feed data database for dairy diet information, determining feed amounts at the state level to derive a total mixed ration (TMR) recipe at the state level. TMR, though not an input that we include directly in emissions calculations, enables the quantification of neutral detergent fiber (NDF) for dairy cows - NDF is a direct input to the enteric emissions calculations for dairy cows.

An example diet for one state (Michigan) is detailed in Table 2. The four main feed components, equal to 90.6% of the TMR, are corn silage, alfalfa hay, other hay, and corn.

Table 2. The total mixed ration (TMR) fed to the dairy cows in our Michigan dairy analysis

Feed type	Percent of TMR	CP	NDF
Alfalfa Hay	25.95%	19.2	41.6
Almond Hulls	0.00%	6.5	36.8
Canola Meal	1.73%	20.5	17.8
Corn	10.61%	9.4	9.5
corn silage	38.74%	8.8	45
Corn DDGs	4.33%	29.7	38.8
Inedible Tallow	1.22%	NA	NA
Meat & Bone Meal	0.07%	95.5	NA
Other Hay	15.28%	18.4	49.6
Soybean Meal	0.30%	NA	NA
Soybean Seeds	0.26%	NA	NA
Soy Hulls	1.02%	13.9	60.3
Soybean Oil	0.50%	NA	NA
TMR	**100%**	**14.0**	**39.4**

To date, we were unable to find this data in a format that allowed for simple parsing, so all data from IFEEDER was manually transcribed into the inventory spreadsheet.

Feed nutrient analysis (crude protein, CP % , and neutral detergent fiber, NDF %) comes from the National Academy of Sciences nutrient feed analysis report (NAP, 2001). Utilizing the IFeeder data allowed us to vary diets by state, better reflecting emissions as they vary across the U.S.

CO_2eq

Greenhouse gasses each have a distinct global warming potential (GWP). GWP is a measurement of each gasses' effectiveness at trapping heat within the Earth's atmosphere. Since each GHG has a unique GWP, it's common to convert all emissions from GHGs into carbon dioxide equivalent units (CO_2eq), as shown in Table 3. This conversion to a common unit allows for easier estimation and interpretation of all emissions. We have reported emissions throughout this paper in terms of carbon dioxide equivalents (CO_2eq). To convert N_2O and CH4 to CO_2eq, we used the 100-year global warming potential values: 28 for CH_4 and 265 for N_2O, which are the most recent and recommended multipliers by the IPCC, 5th Assessment Report (AR5)[2].

Table 3. GWP Table

GHG	Formula	100-year GWP (AR5)
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

Enteric Emissions

Rationale

Enteric fermentation represents roughly 40% of GHG emissions from the livestock sector (Gerber, 2013). Enteric emissions, therefore, have a large mitigation potential for reducing emissions and improving sustainability within the livestock sector. While maximizing gross energy intake and nutrient quality for animals is one approach for reducing emissions on a per unit basis, other approaches like feed additives can potentially further reduce

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[2] https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

emissions from enteric fermentation (Honan et al., 2022). We calculated baseline enteric EFs by state and animal types using publicly available state level data in order to determine emissions profiles across CONUS.

Dairy

The enteric model used by ManureDNDC (and for calculating enteric emissions within this project) is based on an updated California Dairy Emission Model (CADEM, a CA specific version of the ManureDNDC model) for a report created for the California Air Resource Board (CARB) and utilizes *dry matter intake (DMI)* and *neutral detergent fiber (NDF)* for calculating enteric emissions (eq 1). The enteric model was chosen for the CARB model based on improved goodness of fit (GOF) stats to similar enteric CH4 models (Moate et al., 2011, Moraes et al., 2014, Niu et al., 2018). Over 1,436 observed values, the equation provides significant results with an R2 = 0.79 and p < 0.01). Heifers and replacement animals utilize equation 2, which only uses DMI as an input for calculating enteric emissions.

$$eq\ 1\ lactating\ cow\ enteric_{CH4} = 49.5 + (12.1\ x\ DMI) + (2.57\ x\ NDF)$$
$$eq\ 2\ heifer\ \ enteric_{CH4} = 16.64\ x\ DMI + 0.86$$

Table 4. shows the DMI, CP, and NDF values for 3 states - CA, MN, and NY. The DMI is consistent across all states, and the IFEEDER data informs the crude protein and NDF values, which are unique per state.

	State		
Variable	CA	MN	NY
DMI (kg/cow-day)	23	23	23
CP (%)	13.8	14.1	13.6
NDF (%)	37.4	37.6	38.4

Table 4. Enteric emissions inputs for CA, MN, and NY. All others in Inventory.

Beef

An updated CADEM equation for enteric emissions from beef was not available at this time, so the EPA livestock inventory approach (eq A-25) was used for calculating enteric emissions from beef. Gross energy intake (GEI) values were provided at the state level (EPA, table A-148) for the various beef animal categories, while methane conversion (Ym) values were taken from A-146 and A-147 for foraging and feedlot beef animals respectively. The Ym value used was 3.9% for feedlot beef and 6.5% for not-on-feedlot beef animals, reflecting variation in diets between the respective animals.

Equation A-25, adapted to annual

$$CH4\ (kgCH4/animal - year) = (GE\ x\ Ym \div 55.65)\ x\ 365$$

Manure Emissions

Rationale

Manure emissions can comprise a significant portion of livestock based emissions, especially when manure isn't deposited directly on pasture. These manure emissions can represent 35-65% of livestock based emissions depending on the management used (FAO, 2013; Gerber, 2013). This large share of emissions from manure is due to manure accounting for both GHG emissions from manure storage (10-25%) and application of manure to fields (25-40%) for associated fodder production (FAO, 2013). Further, manure results in both CH4 and N2O emissions based on how the manure is stored and at what point in the manure continuum it is being examined, where changes in manure management that lower the emissions of one GHG may increase the other (Chadwick et al., 2011). For example, alterring how manure is managed in the system from a lagoon to dry manure management might reduce CH4 emissions, but increase N2O emissions. Therefore, emissions of both, while also tracking the duration of manure storage and other factors, like climate, that can affect emissions is vital. To estimate manure emissions, the amount of manure created (volatile solids and nitrogen excreted), how the manure is handled or the waste management system (WMS), and climate and system related methane conversion factors (MCF) are needed in order to derive manure based emissions (EPA, 2021).

Beef & Dairy

Equation A-35, CH4 emissions for all animal types

$$CH4\ (kgCH4/animal - year) = 0.662\ x\ VS_{excreted}\ x\ MCF\ x\ B_o$$

where 0.662 is the density of CH4 at 25C (kgCH4/m3 CH4) used for converting to CH4 emissions, $VS_{excreted}$ is the volatile solids excreted per animal (kg/yr, from EPA A-164), MCF (EPA Table A-168,A-169) is the methane conversion factor which can reflect methane conversion rates by manure management type, animal, and climate, and B_o (EPA Table A-162) is the maximum CH4 producing capacity of the manure management in each waste management system (WMS). As multiple WMS and animal types can exist within a state, the state level values are the weighted sum of all WMS and animal type categories.

Waste management system allocation used EPA Table A-165 in order to allocate state level VS amounts for beef and dairy cows respectively, with the sum across WMS-states from equation A-35 providing the state level inventory values.

Table 5. Example manure CH4 calculation for a lactating dairy cow in California.

variable	**units**	**value**
Excretion and CH4 potential		
Volatile solids	kg/cow-year	2861
N excreted	kg/cow-year	159
Bo	m3 CH4/kg VS	0.24
Methane Conversion Factors by WMS		
MCF dry	%	1.5
MCF liquid slurry/deep pit	%	34
MCF lagoon	%	75
MCF digester	%	50
WMS allocation of manure		
% dry	%	29
% liquid	%	12
% lagoon	%	54
% digester	%	0
% pasture/daily spread	%	5
Manure CH4 for Lactating cow in CA		
Lactating cow manure CH4	kgCH4/cow-year	204.62

Results

State level enteric and manure emissions, for beef and dairy, are available in the *inventory* tab of the spreadsheet, while detailed values, broken down by animal category are within the dairy and beef specific manure and enteric tabs. Total state level dairy emissions are represented in Figure 1, which provides a state level summary of dairy emissions by state. As

Figure 1 is a sum of emissions at the state level, it reflects animal numbers, management systems, and climate impact on emissions.

Dairy emissions

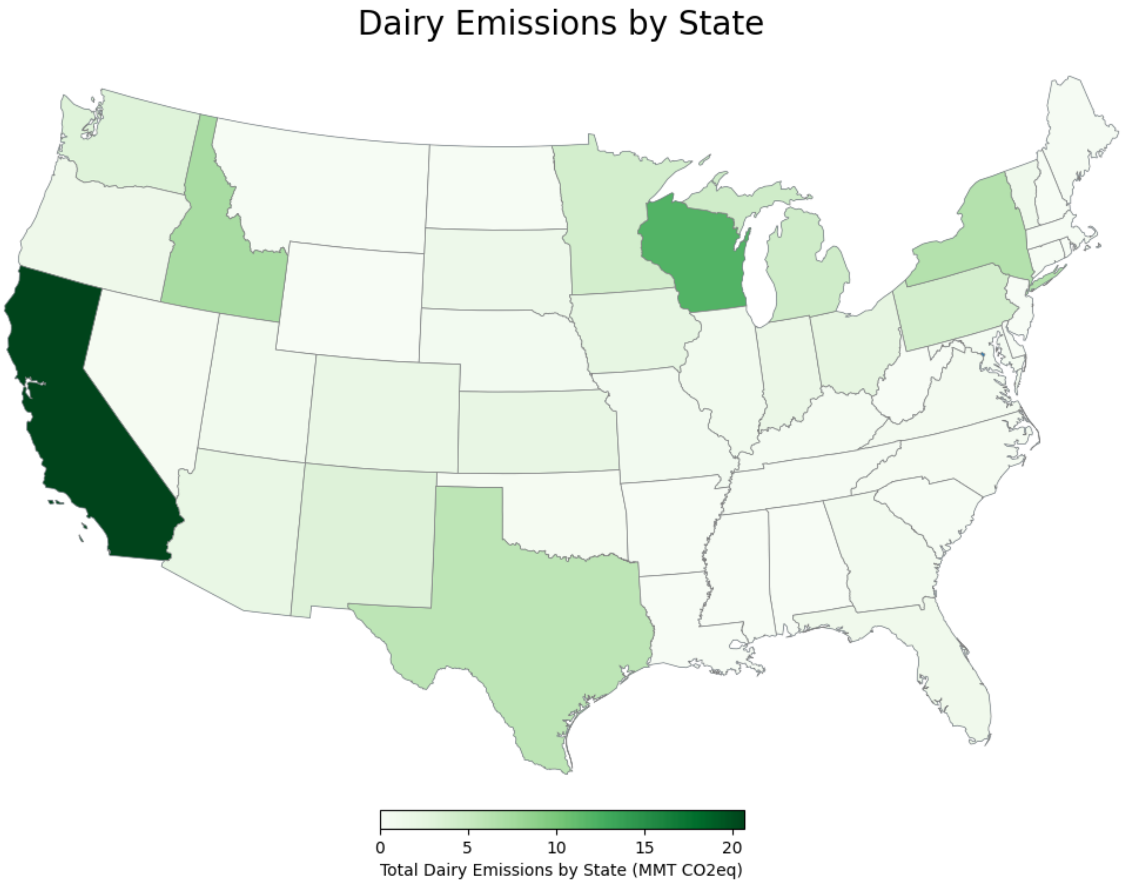

Figure 1. Total (enteric + manure) dairy emissions by state.

Enteric

The ManureDNDC dairy enteric equation generally provides a comparable value to that of the enteric equation used in the EPA report as shown in Table 6.

Table 6. Updated enteric emissions values (orange) in comparison to source data (purple) for CA/MN/NY. All others in Inventory.

	State		
Variable	CA	MN	NY
DMI (kg/cow-day)	23	23	23

CP (%)	13.8	14.1	13.6
NDF (%)	37.4	37.6	38.4
mDNDC EF (kg CH4/cow-year)	**156.3**	**146.6**	**147.3**
EPA EF (kg CH4/cow-year)	**150**	**138**	**162**

Enteric emissions did not vary much by state on the basis of kg CH4/cow-year; the differences in state-level emissions shown in Figure 1 and figure 3, therefore, are in large part a reflection of animal numbers within the state, rather than any significant differences in enteric emissions in the forage and feed inputs, leading to large variation between states (note that figure 1 shows manure+enteric emissions, so lack of enteric variability is best seen in figure 3) . Variability was much lower between states using IFEEDER inputs and ManureDNDC equations than from the EPA equation (Table 7).

Table 7. Comparison of CONUS dairy enteric EF values (kgCH4/cow-year) between ManureDNDC and the EPA equations.

statistic	ManureDNDC	EPA
Standard deviation (stdev)	1.17	13.03
min	145.65	107
max	149.59	169
avg	147.88	145.63

Updating nutritional values of feeds on a state or regional basis could bring more variability back into that equation. The ManureDNDC equation could also be updated to better reflect animal conditions, energy use, and lifestyles - that affect energy consumption and use - that are better accounted for in the EPA equation.

Manure

The manure-based emissions for dairy operations did vary by state due to differences in volatile solids, nitrogen excretion, waste management systems, and state climates (Figure 2). For instance, Nevada had the highest (224.04 kg CH4/cow-year) per cow manure emissions for lactating cows, while West Virginia had the lowest (65.9 kg CH4/cow-year). This is largely a reflection of the percent of manure managed in lagoons, a state level high of 61% in Nevada and state level low of 13% in West Virginia, respectively. With lagoons having the highest MCF of any WMS, or largest CH4 emissions of any manure management system, the high level of use of lagoons in Nevada has a large impact on resulting emissions in the state. Results like this provide a suggested pathway for mitigation within the systems or states. For Nevada, looking into the potential for swapping manure management systems to lower MCF manure management practices, or working to incorporate more covers on lagoons and/or CH4 flare or capture technology onto lagoons suggests a high ROI on reducing CH4 emissions. Obviously, the capital costs, social dynamics, and Nevada specific farming conditions would need to be a large part of the conversation about potential implementation of any practices.

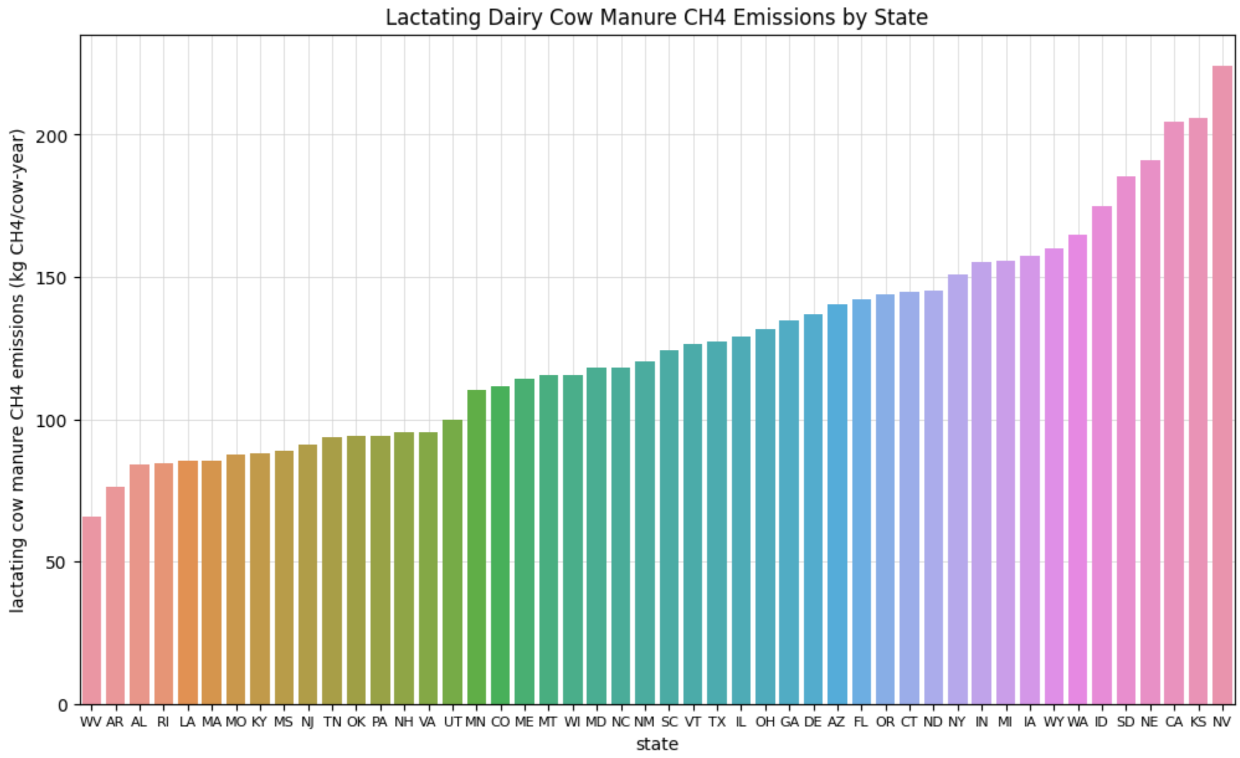

Figure 2. Manure CH4 EF by state from dairy farms for lactating cows. Emissions vary by state based on volatile solid, nitrogen excretion rates, as well as by waste management system and respective climates by state.

As emissions are a function of manure management systems, climate, and other management decisions like feed or grazing, we further calculated a weighted animal average emission, shown in figure 3 and in the *Carbon Intensity* tab of the workbook. The weighted average reflects the number, and various stages or ages, of animals within a state and the associated emissions at each stage. As replacement animals is an especially important variable within dairy farms for GHG emissions, this weighting across animal classes provides an estimate of total emissions on a per animal basis in the state, while reflecting the replacement animals needed in the system. Using this figure can provide some insights towards emission intensity per state, reflective of animal numbers and types within the state. For example, comparing Arkansas (AR) where 23% of manure is managed in lagoons and 47% based in grazing to that of South Dakota (SD) where 54% of manure is managed in lagoons and only 14% is grazing we can see that Arkansas has a much lower carbon intensity than South Dakota (Figure 3). This is despite Arkansas being a warmer state with greater potential for CH4 production from manure management (e.g., MCF of 1.5 and 75 for dry manure and lagoon in AR compared to 1 and 69 in SD, respectively). This shows that climate impacts, taken in consideration with management decisions, are important for deriving accurate emissions estimates.

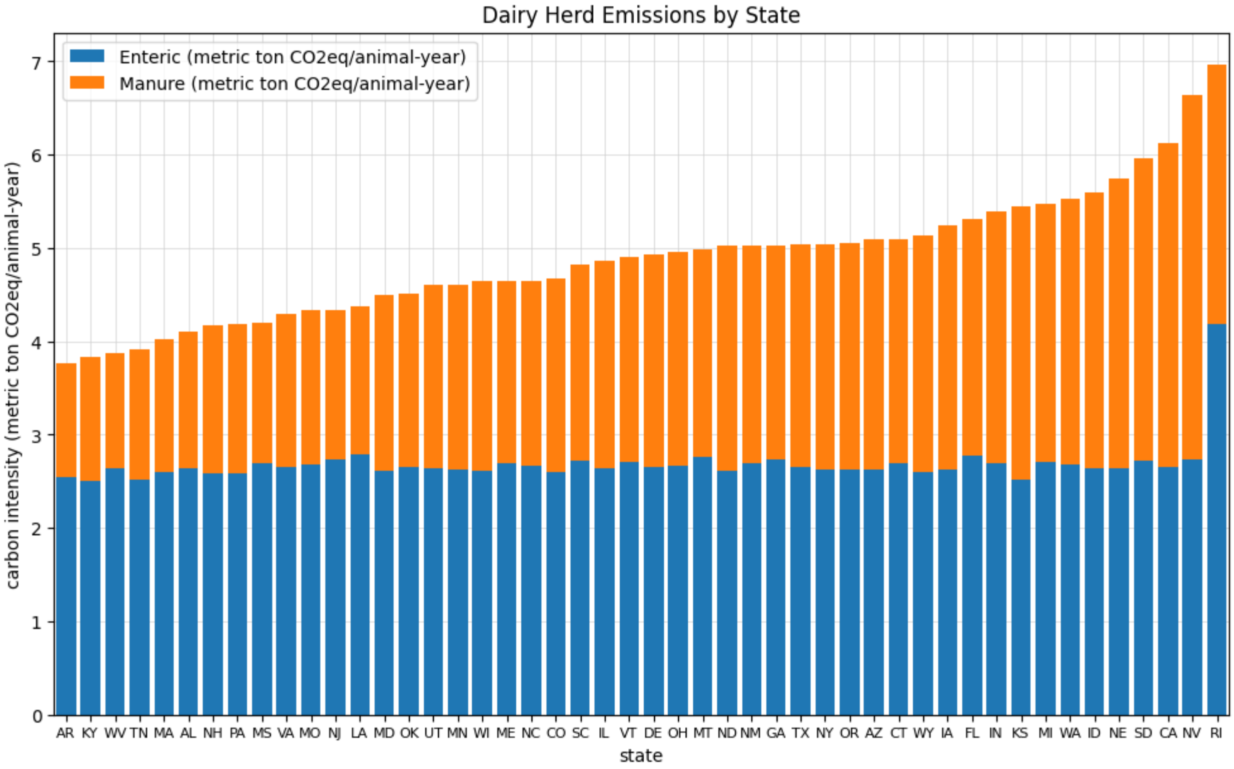

Figure 3. State level emissions from dairy broken down by enteric (blue) and manure (orange) origin sources. The value is animal class weighted across the various dairy age/types to represent emissions on a per animal basis, across all classes (e.g., if dairy milking cows comprise 70% of animals in state and heifer cows 30%, total emissions from dairy cows would be multiplied by 0.7 and heifer cows by 0.3 to get the ‘weighted animal classification’ value shown above). Animal numbers for Rhode Island suggest that only milking cows are present, and thus enteric emissions are larger than other states given the higher enteric CH4 emissions from milking cows - this is very likely just a bad counting of animals from EPA and USDA sources given the small state and low animal numbers in the state, and thus not being of much importance for a national level inventory.

Beef emissions

Total state level beef emissions are shown below in Figure 4, which provides an idea of emissions spatially across states in CONUS.

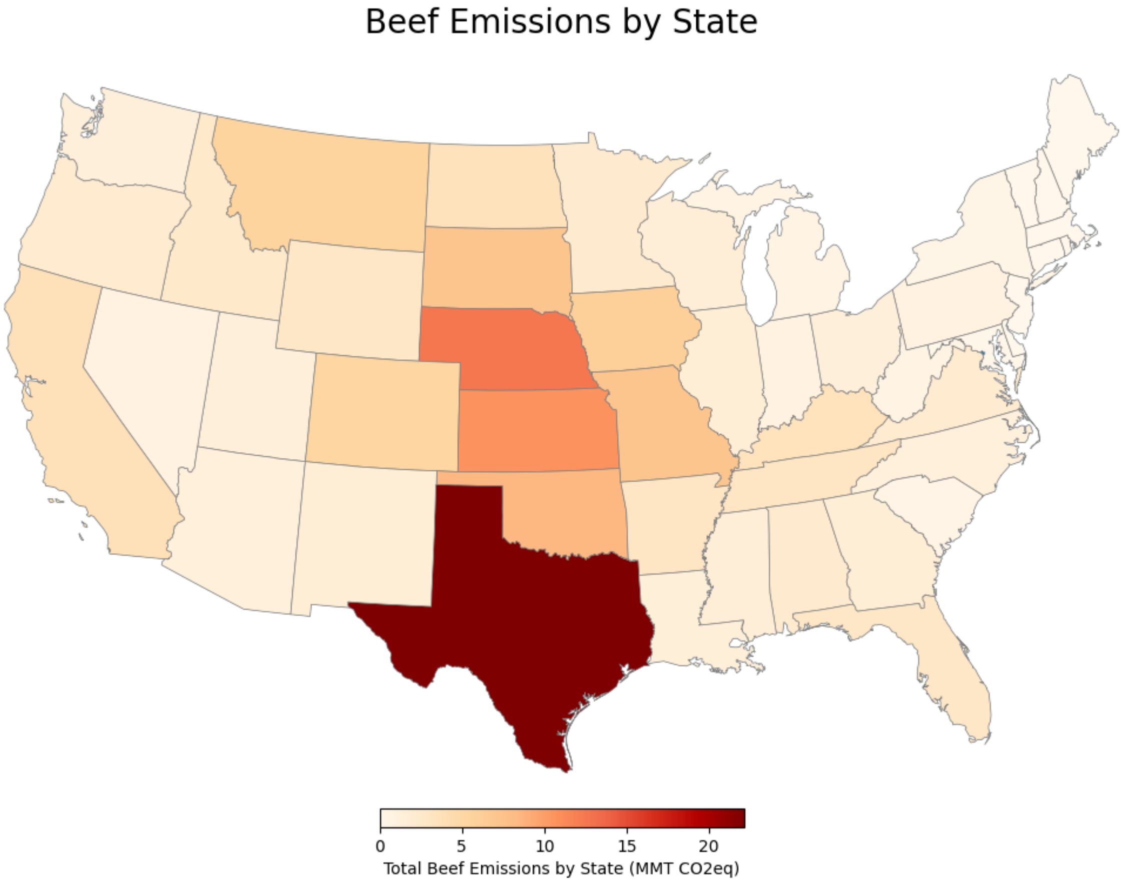

Figure 4. Beef manure and enteric emissions by state.

Enteric

While enteric emissions for beef did vary by state (reflecting different GEI and animal activity), the variability is not quite as large as that of dairy cows (figure 5). In terms of factors contributing to the variability: the gross energy intake (GEI) was unique per state for beef animals, whereas the methane conversion rate (Ym) was managed the same across states for this inventory, with the exception of beef lot animals that have a Ym of 3.9 compared to other beef animals of 6.5% (see Table 7 for GEI, Ym, and EF values for three states in CONUS).

Table 8. Beef cow enteric emission factors for select states.

	State		
Variable	CA	MN	NY
GEI (MJ/day)	85.9	78.7	80.7
Ym (%)	6.5%	6.5%	6.5%
ManureDNDC EF (kg CH4/cow-year)	**100.37**	**91.91**	**94.28**

*note that the Ym of 6.5% applies to non-feedlot beef animals, while feedlot animals would have a Ym closer to 3.9% - reflective of variations in diet, and higher forage in non-feedlot animals.

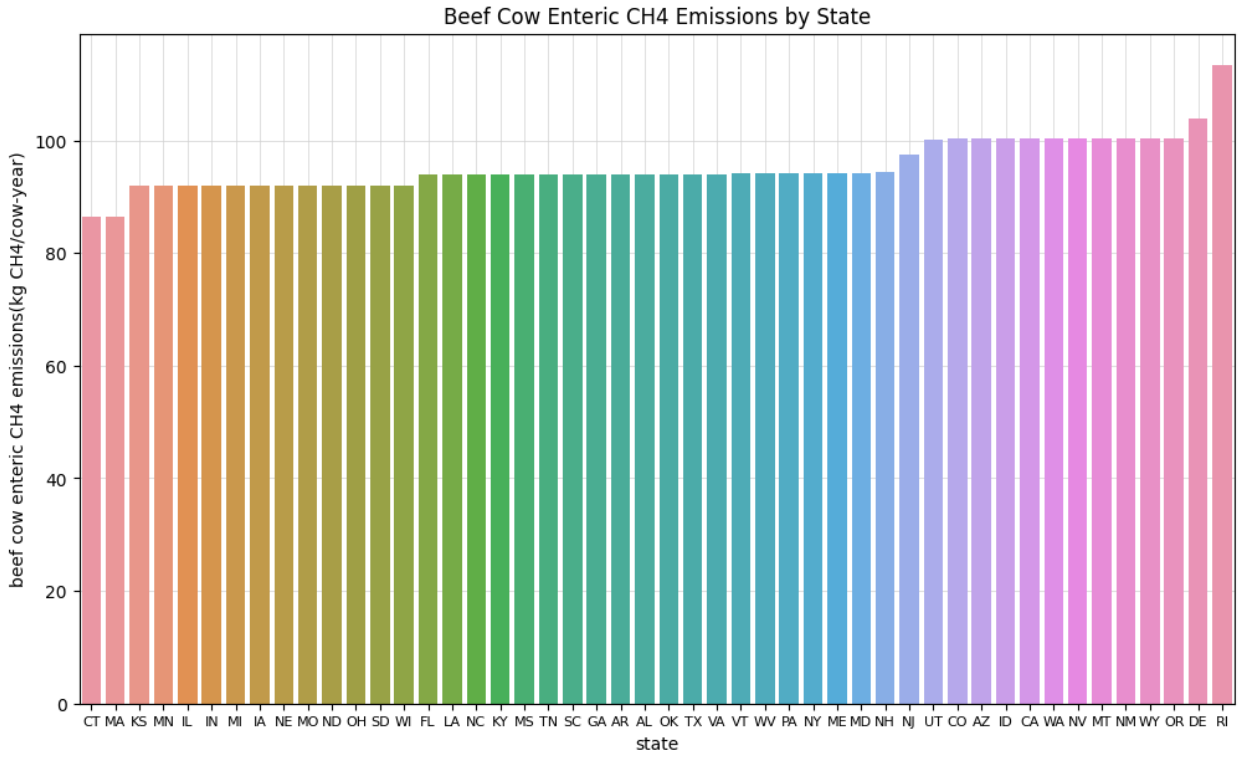

Figure 5. Beef cow enteric emissions by state (kg CH4/cow-year).

Updating Ym values at a regional or state basis (should we be able to obtain that data through data partnerships or research studies) would likely better reflect differences in animal diets and characteristics as well as increase variability in enteric results and represents a possible area of improvement.

Manure

Compared to dairy, beef emissions are less variable for manure management, as grazing plays a large role in beef production - and thus there is less manure storage in beef systems and subsequently lower CH4 emissions from manure. This aligns with the expected variability as defined by the EPA (Table 9). Additionally, beef manure that is managed in feedlots is almost exclusively managed in dry lots, which has a much lower MCF than some other WMS found in dairy operations.

Table 9. EPA statistics on variability in beef cow enteric emissions (kg CH4/cow-year).

Statistic	**EPA**
Standard deviation (stdev)	4.63
min	86.43
max	113.30
avg	95.34

Looking at total carbon intensity for beef operations (figure 6), enteric emissions are clearly the main driver of emissions. Given larger use of grassfed operations (and thus natural manure deposition or daily spreading of manure), and use of dry lot manure management, compared to more lagoon heavy dairy operations, for those confined beef operations, manure emissions represent a much smaller percentage of emissions in beef systems. Variations in enteric emissions are then largely a representation of animal classes and percentages per classification, as well as GEI variations between animals.

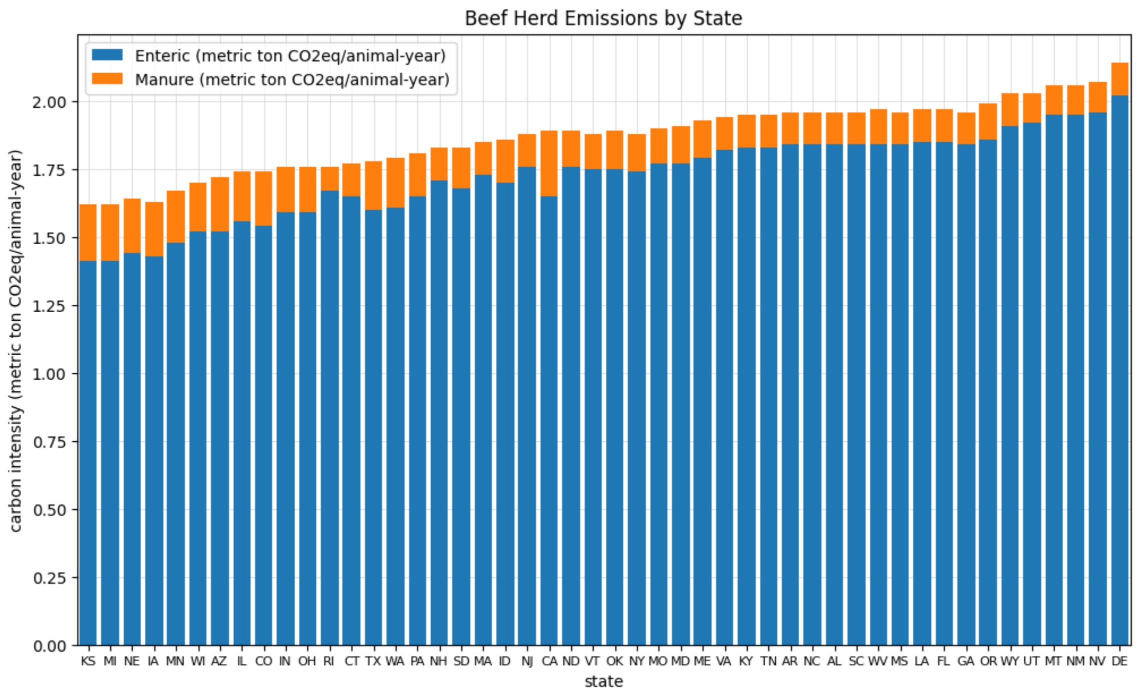

Figure 6. State level emissions from beef broken down by enteric and manure origin sources. The value is animal class weighted across the various beef age/types to represent emissions on a per animal basis, across all classes (e.g., if beef cows comprise 70% of animals in state and feedlot cows 30%, total emissions from beef cows would be multiplied by 0.7 and feedlot cows by 0.3 to get a ‘weighted animal classification’).

Reflections and the livestock roadmap

As we look back on the work done for this livestock inventory, we can highlight a few key learnings. One is that in order to at least establish baseline values for CONUS, it is imperative to source streamlined data and consistent data points across the area of interest. Given the volume of inputs required for quantifying enteric and manure emissions for beef and dairy cattle, we were limited in sources that would provide both the granularity of data that we needed as well as the standardization and interoperability of that data across all of CONUS. Therefore, we relied on two primary data sources (EPA and IFEEDER), from which we transcribed significant emissions inputs, which was a non-trivial component of the inventory generation process, and is a critical foundation on which future inventories can be built upon. Both the values reflected in the EPA report and IFEEDER data are generally available at the state level and further reflect other characteristics within a state or region (e.g., climate impacted EF for CH4 emissions from manure). This represents a big improvement over static EFs and data tables. The output is a dynamic, interactive, and responsive workbook in which data points are interconnected, such that an update to input values will automatically update associated EFs and total emissions. This dynamic table, or dynamic EF approach, allows for setting a higher data quality inventory than simplistic tier 1 methods that would be applied evenly across all scenarios.

For example, now that the state-level emissions baselines have been established in an interactive location, updates can be made whenever data is available to further refine emissions inputs at a state level. Some states (like California) have robust public datasets for dairy operations, in particular, which can be incorporated into the inventory workbook we have. We cannot expect the level of data availability to be consistent across all states, however, so we can leverage baselines (derived from EPA and IFEEDER datasets) to quantify emissions in a consistent manner.

Keeping in mind the goal of this project was to - *further refine enteric and manure emission factors at a state level in the United States* - this report shows improvement to tier 1 EF with a dynamic EF structure that also reflects improved data sets (e.g., IFEEDER) compared to other inventories that have been completed.

Based on the values provided in this dynamic EF inventory, and looking forward to how this data can be further improved, expanded on, and most importantly, help facilitate carbon intensity reductions within the livestock sector, we can highlight several initiatives that Regrow is working on and would be interested in partnering on;

- Presently, Regrow is building out a framework for developing, calibrating, validating, and deploying our ManureDNDC model at scale. In anticipation of that work, we prioritized inputs and equations in this inventory exercise that have transference to the process-driven model, particularly for dairy enteric emissions. While the dynamic EF shown in this workbook are an improvement from tier 1 methods, manureDNDC is a tier 3 method that would further improve estimates. For example, while a MCF value for lagoon is climate specific, it does not reflect management decisions on a farm of when that manure will be spread, and thus when emissions, and the quantity of emissions, will occur. Modeling with manureDNDC at a daily time step therefore presents an opportunity to provide an improved region or even farm specific MCF value for a manure management system.
- This inventory further provides a baseline of emissions, and while interventions [to reduce emissions] were not within the scope of this report, the first step for identifying potential areas for improvement and opportunities for the greatest return on investment (ROI) for reducing emissions are closer thanks to baselines being created.
- Regrow is partnering on several projects with CPGs, data providers, and universities to further improve the ManureDNDC model as well as prototype MRV like data integration and emissions quantification projects