THESIS

GWP* OF U.S. BEEF AND DAIRY SYSTEMS

Submitted by

Erick Molina Plaza

Department of Animal Sciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2023

Master's Committee:

Advisor: Jasmine Dillon

Shawn Archibeque
Scott Denning
John Sheehan

ABSTRACT

GWP* OF U.S. BEEF AND DAIRY SYSTEMS

Global warming potential (GWP) is used to quantify the impact that greenhouse gases (GHG) have on the warming of the Earth's atmosphere relative to carbon dioxide (CO_2). GWP* is a metric that is used to better quantify short-lived climate pollutants (SLCP) such as methane, hydrofluorocarbons, and sulfur dioxide. GWP* allows SLCP to be more consistently expressed by equating a change in the emission of the SLCP to a one-off pulse emission of CO_2. Therefore, GWP* can be positive or negative. The objective of this work was to compare the GWP* and GWP_{100} for U.S. beef and dairy systems using livestock methane emissions data from the Food and Agriculture Organization (FAO) and the Environmental Protection Agency (EPA). Total methane emissions for this study are the sum of enteric and manure methane emissions. GWP_{100} was greater than GWP* for both beef and dairy systems using both datasets, with the exception GWP* for dairy using the EPA data. Dairy GWP* calculated using the EPA data was lower than GWP_{100} from 1990–2000, after which point on it became greater than GWP_{100} and continued increasing annually, because the emission factors used by the EPA increased annually, and the difference between weighted emissions from that year and the weighted emissions from 20 years prior surpassed the current emissions used in GWP_{100}. Overall, the GWP* of EPA dairy increased by 507% from 1990–2020. The primary drivers of the differences in GWP* and GWP_{100} with the EPA dataset are the use of methane emission factors for manure methane, which increase yearly, and the use of a larger dairy population estimate than FAO. The EPA emission factors increase yearly based on the trend towards larger farm sizes managing more

liquid manure, therefore produce more manure methane emissions. The dairy GWP* using EPA data was greater than the beef GWP* every year, despite greater total methane emissions for beef than for dairy, because the average rate of change for dairy (29.8 kt of CH_4/yr) was greater than the average rate of change for beef (9.4 kt of CH_4/yr). Accounting methods play a key role in the amount of methane emissions that are calculated, and thus how GWP_{100} and GWP* are calculated. The EPA larger population estimate and annual increase in manure methane emission factors led to greater GWP* and GWP_{100} values for the EPA data than for the FAO data for both beef and dairy systems. Data source is critical to the policy implications of GWP* and GWP_{100} for livestock systems, as evidenced by the differences in GWP* and GWP_{100} results between datasets.

TABLE OF CONTENTS

1 INTRODUCTION

In 2021, methane accounted for 12% of total greenhouse gas (GHG) emissions in the U.S., of which, 33% came from enteric fermentation and manure management (25% and 8%, respectively) (EPA, 2023). Beef and dairy cattle were responsible for approximately 96% of enteric methane emissions and manure methane emissions (71% and 25%, respectively) (EPA, 2023). As for ruminants, this means that beef and dairy cattle are the main contributors of livestock methane emissions to the U.S. GHG inventory.

Global warming potential (GWP) is a metric used to estimate the impacts of different GHG on climate. More specifically, a GWP is the measure of how much energy the emission of 1 ton of a GHG will absorb relative to the emission of 1 ton of CO_2 in a given time period (IPCC, 2006; EPA, 2023). The bigger the GWP value is for a GHG, the more warming it creates in the Earth's atmosphere when compared to CO_2 over that time period. GWPs are reported in 20-, 50-, 100- and 500-year time periods, with 100 years being the most common time period used for GWP (GWP_{100}).

To compare the emissions of methane to carbon dioxide, total methane emissions are multiplied by the GWP value of methane for the chosen time period, in the case of this study, the GWP_{100} for methane is 28 (IPCC, 2014). Recent studies have concluded that while GWP_{100} is a valuable metric for long lived climate pollutants (LLCP) such as nitrous oxide (atmospheric lifetime of 121 years), it is not fitting when using it to compare short lived climate pollutants (SLCP) such as methane, which lasts approximately 12.4 years in the atmosphere (Allen et al., 2018; Cain et al., 2019; Lynch et al., 2020; Smith et al., 2021, IPCC, 2014). These studies proposed a newer metric, GWP*, which better accounts for SLCP and their impact on the Earth's warming. A few studies have since applied GWP* to evaluate the climate impact of U.S.

livestock production. Place et al. (2022) argued that GWP* provides a more appropriate quantification of methane emissions in the U.S. dairy industry. Liu et al. (2021) found that using GWP* to calculate methane emissions of the U.S. cattle industry indicated that the cattle industry had not contributed to additional climate warming in the U.S. since 1986. Beck et al. (2022) found that the GWP* of beef and dairy systems in the U.S. were lower than GWP_{100}, but that data source and GHG accounting method influenced the findings.

The purpose of this study was to calculate and compare the GWP* and GWP_{100} of U.S. beef and dairy systems using enteric and manure methane emissions from FAO (FAO, 2022) and (EPA, 2023).

2 LITERATURE REVIEW

2.1.1 Sustainability

In 1988, the United Nations' World Commission on Environment and Development (WCED) published a report titled the Brundtland Report (Keeble, 1988), which defined sustainable development and created guidelines for economic development with social and environmental impacts in mind. Sustainable development was defined in the report as the ability to meet the needs of those of us in the present, without compromising the needs of those in the future, taking into consideration nature's finite resources (WCED, 1987). The importance of this report resonates today due to the increasing demand society has for food, water, and shelter as global population increases and dietary preferences evolve (Farooq et al., 2019). This trend creates significant pressure on agricultural demand. In 2009, the average global, daily per capita protein consumption was 68 g, which is more than ⅓ higher than the protein requirement for adults (Ranganathan et al., 2016). Beef is the most resource-intensive source of protein produced, 10–50 times higher than that of other animal protein alternatives as well as plant-based protein (Eshel et al., 2018). Global meat consumption increased by 58% from 1998–2018, with population growth and per person consumption growth accounting for 54% and 46%, respectively, of this increase (Whitnall and Pitts, 2019). Therefore, increasing the production of food products such as beef must be made without exhausting resources that will be needed for in the future.

2.1.2 Methane and Climate Change

Earth is habitable due to the presence of gases that trap long-wave radiation emitted from its surface. This is referred to as the greenhouse effect (Milich, 1999). Methane, carbon dioxide and other greenhouse gases affect the Earth's warming by absorbing long-wave radiation emitted from the surface and reradiating it back to the surface, because they absorb little to no solar radiation. This is what causes the additional warming of the Earth's atmosphere (Mitchell, 1989). Methane is the most abundant organic chemical found in the Earth's atmosphere (Cicerone and Oremland, 1988). Its chemistry has a major role on the global atmosphere because it decreases the amount of ozone in the troposphere and stratosphere, increases the amount of water vapor in the stratosphere, and decreases amount of hydroxyl in the troposphere (Wuebbles and Tamaresis, 1993). As methane oxidizes in the atmosphere, it produces atmospheric carbon monoxide and formaldehyde (Wuebbles and Tamaresis, 1993). The increasing concentration of methane in the atmosphere is concerning due to the potential effects that it can have on the climate as well as the atmosphere's chemistry (Wuebbles and Tamaresis, 1993).Therefore, understanding how methane affects global warming is of upmost importance.

Methane is emitted from several agricultural sources including enteric fermentation, manure management, rice cultivation, and field burning of agricultural residues. In 2021, methane accounted for 12% of GHG emissions in the U.S. Of which enteric and manure methane emissions were responsible for 27% and 9%, respectively (EPA, 2023). Cattle release methane, a greenhouse gas, through ruminal fermentation as well as manure management. Enteric methane is a by-product of anaerobic fermentation in the reticulo-rumen. In the rumen, bacteria, protozoa, and fungi thrive to create an anaerobic environment (Patra, 2012). Fermentation of feed in the rumen produces volatile fatty acids (e.g., acetate, propionate, and butyrate), the ratios of which, together with the population of protozoa, drive methane production. Feeding cattle diets containing high levels of non-structural carbohydrates (for example, grains and higher quality forages) or starchy feeds will increase propionate production while decreasing acetate production, thus reducing the production of enteric methane in the rumen (Patra, 2012). Enteric methane production also varies with feed intake, forage processing, lipid addition, types of carbohydrates, and use of other methane inhibiting compounds (Johnson and Johnson, 1995). In addition to these factors, the length of time the animal is on feed plays a key role due to the animal consuming more feed for a longer period of time, which results in more emissions being produced (Pelletier et al., 2010).

2.1.3 Greenhouse Gas Emissions and Environmental Footprints of U.S. Beef and Dairy Systems

Cattle fed high-quality diets, intensively managed for production in the shortest amount of time possible could see their carbon footprints decrease (Heflin et al., 2019). This indicates the role that days-on-feed plays when it comes to carbon footprint. The more intensive feeding and managed beef cattle are, the smaller the carbon footprint will be when compared to non-intensive, *ad libitum* beef finishing systems. Not only does diet affect the carbon footprint, but rotational grazing and high animal and land productivities can lower the carbon footprint as well (Nieto et al., 2018).

The GWP_{100} of dairy systems has been calculated to assess the environmental impacts of milk production in the U.S. (Thoma et al., 2013b; Thoma et al., 2013a; Henderson et al., 2023). Thoma et al. (2013) calculated that the total GWP from cradle–to–grave of the U.S dairy industry in 2007–2008 was 2.05 kg CO_2 equivalent per-kg of consumed milk. Of which approximately 1.9% of U.S. GHG emissions come from the entire dairy sector (Thoma et al., 2013b). Henderson et al. (2023) found that methane was responsible for 65% of GWP impacts from the agricultural production of milk from farm to gate. These studies have found that the dairy industries biggest contributor of GHG emissions are manure management, enteric fermentation, and feed production (Thoma et al., 2013b). Manure management practices impact the methane production in dairy systems. Anaerobic lagoons produce significantly more methane emissions than other systems like dry lot and solid storage (Thoma et al., 2013b).

*2.1.4 GWP and GWP**

Greenhouse gases can be classified into two groups: long-lived climate pollutants (LLCP) and short-lived climate pollutants (SLCP) (Smith et al., 2012; Pierrehumbert, 2014). The atmospheric lifetime of SLCP range from a few weeks to fifteen years. Long-lived climate pollutants are GHG that have an atmospheric lifetime ranging from hundreds to thousands of years. An example of a LLCP is carbon dioxide (CO_2). The IPCC states that carbon dioxide's atmospheric lifetime cannot be directly defined due to the variability in uptake rates caused by different removal processes. Taking this into consideration, the IPCC estimates carbon dioxides atmospheric lifetime ranges from five to two hundred years (IPCC, 2018). Methane is an SLCP with an atmospheric lifetime of 12.4 years. There are other LLCPs such as hydrofluorocarbon-23 (HFC-23) which can last 3200 years in the atmosphere as well as chlorofluorocarbon-13 (CFC-13) which can last 640 years (IPCC, 2018). The most abundant LLCP in beef production systems is nitrous oxide from manure (Waldrip et al., 2020).

Climate models have been developed to understand the impacts of GHG on climate as atmospheric GHG concentrations have increased by predicting the behavior of weather patterns (IPCC, 2007). Global warming potential (GWP) is a metric developed by the Intergovernmental Panel on Climate Change (IPCC) in 1990 (IPCC, 1990). The IPCC was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). Its purpose is to regularly assess scientific data regarding climate change and its impact on the environment. Reports written by the IPCC are used to support climate policies (IPCC, 2022). The purpose of GWP and a related metric, GWP*, is to compare the impact of an additional emission of a GHG on the atmosphere to that of CO_2 over a specific time horizon. GWP compares the impacts of different GHG relative to CO_2 using the radiative forcing (RF) of each greenhouse gas. Radiative forcing is the difference between incoming and outgoing radiation in the Earth's atmosphere, specific to each gas (Smith and Wigley, 2000). The energy the Earth absorbs must be emitted equally to space in due time following the basic laws of thermodynamics (Mitchell, 1989). If incoming radiation is more than the outgoing radiation, this will result in a positive RF, meaning Earth will be warmer. If the outgoing radiation is more than the incoming radiation this will result in a negative RF, meaning that the Earth will be cooler (IPCC, 2007).

GWP is calculated as:

$$\mathrm{GWP}_i(\mathrm{H}) = \frac{\mathrm{AGWP}_i(\mathrm{H})}{\mathrm{AGWP}_{\mathrm{CO_2}}(\mathrm{H})} = \frac{\int_0^{\mathrm{H}} \mathrm{RF}_i(t)\mathrm{dt}}{\int_0^{\mathrm{H}} \mathrm{RF}_{\mathrm{CO_2}}(t)\mathrm{dt}} \qquad (1)$$

Where:

H = selected time horizon

$\mathrm{AGWP}_i(\mathrm{H})$ = the absolute global warming potential for the GHG

RF_i = the global mean radiative forcing of the GHGi

i = gas being used

$\mathrm{RF}_{\mathrm{CO_2}}$ = the global mean radiative forcing of CO_2

Carbon dioxide is used as the reference gas and all other greenhouse gases are converted to CO_2 equivalents based on their radiative forcing relative to a pulse of CO_2 (EPA, 2022). This is accomplished using Eq. 2:

$$E_{CO_2-eq} = \mathrm{E}_{GHG_i} \text{ x } \mathrm{GWP}_i(\mathrm{H}) \qquad (2)$$

Where:

E_{CO_2-eq} = CO_2 equivalents

E_{GHG_i} = the emission rate of GHG i

$GWP_i(H)$ = the conversion factor of the SLCP

H = the selected time horizon.

GWP can be calculated for any time horizon but is most often reported in 20-year, 100-year, or 500-year time horizons (GWP_{20}, GWP_{100}, GWP_{500}) (IPCC, 2007). For example, the GWP of methane is 86 for a twenty-year time period and 34 for a one-hundred-year time period. This means that methane has an impact on climate that is 86 and 34 times greater than CO_2 over a 20-year and 100-year time period, respectively (IPCC, 2006).

GWP* is a metric that more dynamically accounts for SLCP such as methane. It has the ability to show a positive or negative effect of SLCP on the GWP of a system by relating the pulse emission of the GHG to the concentration of that gas in the atmosphere at a point in time (Allen et al., 2018; Cain et al., 2019; Lynch et al., 2020; Smith et al., 2021). This means that SLCPs can have a warming or cooling effect. As demonstrated by Allen et al. (2018), CO_2 equivalents and radiative forcing increased and stabilized over time with a GWP* calculation that scales with the current flow (rate of emission) multiplied by the lifetime of the SLCP. Similarly, warming increased rapidly, then stabilized over time.

GWP* is calculated by the following formula:

$$E_{CO_2-we} = GWP_i(H)\ x\ (r\ x\ \frac{E_{SLCP}}{\Delta t}\ x\ H + s\ x\ E_{SLCP}) \qquad (3)$$

Where:

E_{CO_2-we} = the equivalent of CO_2–warming emissions
$\Delta SLCP$ = the change in impacts of the SLCP emission rate
r = the weighting given to the impacts of changing the rate of SLCP emissions
s = the weighting given to the impacts of the current emissions rate

The values for *r* and *s* are contingent on climate scenarios (vary on the historical emissions of each GHG). The values are estimated using a multiple linear regression equation which includes CH_4 emissions from 1900–2100 (Cain et al., 2019).

GWP* provides a potentially more useful indication of warming when compared to GWP, due to the use of methane emissions regarding its lifetime (Lynch et al., 2020). A recent study compared SLCP emissions using GWP and GWP* to determine which metric yielded more accurate results and found that under GWP* there ss a decline in rate of emissions for an SLCP, which mimics the behavior of temperature responses, and thus GWP* is lower (Allen et al., 2018). Lynch et al. (2020), found that GWP_{100} results in greater values than GWP* due to its inability to account for an increase and decrease in emission rates, whereas GWP* can account for the emissions rates depending on the gas concentrations present in the atmosphere. Liu et al. (2021) found that emissions from cattle production in 2017 totaled 6.5 MMT (Million metric tons) of CO_2-we (warming equivalents) compared to 8.5 MMT CO_2-we in 1975. When comparing the GWP for those years they found that GWP suggested that methane emissions would lead to an increase of 165 MMT CO_2-we to 196 MMT CO_2-we annually, whereas the GWP* results show that methane emissions have not contributed to additional warming like GWP indicates. The difference between GWP and GWP* stems from the rate of decrease in cattle population. From 1961–2017 U.S. dairy cattle population had decreased by 46%, whereas beef cattle population in 2017 had decreased by 30% when compared to 1975 according to data found in the FAO database (Liu et al., 2021). Beck et al. (2022) conducted a study to compare the methane emissions reported by 2 entities (FAO and EPA), found that GWP_{100} resulted in a higher value than GWP* for both FAO and EPA.

Of the two metrics, GWP has more often been used to quantify greenhouse gas emissions from agricultural systems (Smith et al., 2012; Allen et al., 2018; Cain et al., 2019; Lynch et al., 2020; Liu et al., 2021). The use of a newly applied metric, GWP*, provides the ability to better account SLCPs, where GWP lacks. There is a paucity of published data for GWP* of beef and dairy systems (Liu et al., 2021; Beck et al., 2022; Place et al., 2022). The purpose of this thesis is to address this gap in the research by calculating and comparing the GWP* and GWP_{100} of beef and dairy systems.

*2.1.5 Interpretation and Implications of GWP**

The use of GWP* as a metric for reporting the warming impacts of SLCPs can provide great insight into the contribution of livestock towards global warming, but by no means is it perfect. GWP* can better account SLCPs, and thus produce a lower global warming potential, but the interpretation of GWP* can cause problems when it comes to possible mitigation strategies. Del Prado et al. (2023) and Allen et al. (2022) both found that GWP* can provide results that show no additional warming, referred to as climate neutrality, but over longer periods of time GWP* can overstate the additional warming caused by SLCPs. Therefore, interpreting the results of GWP* must be done with caution.

3 MATERIALS AND METHODS

3.1.1 Data Sources

Total cattle population data from 1990 to 2020 were obtained from FAO (FAO, 2023), while beef and dairy cattle population were obtained from the EPA Sinks and GHG Reports (EPA, 2023). Disaggregated beef and dairy population data were not available from FAO. Enteric and manure methane emissions from 1990 to 2020 for beef and dairy were obtained from FAO (FAO, 2023) and EPA (EPA,2023).

3.1.1.1 FAO Methane Emissions Calculations

For the calculations of enteric (Eq. 4, Eq. 5) and manure methane emissions, which are referred to by FAO as "FAO estimated", FAO follows Tier 1 IPCC guidelines for national GHG inventories (IPCC, 2006). Tier 1 is described by the IPCC as a simplified approach that uses default emissions factors obtained from the literature or calculated using IPCC Tier 2 methodology.

$$Emissions = EF_{(T)} \; x \; (\frac{N_{(T)}}{10^6}) \qquad (4)$$

Where:

Emissions = methane emissions from Enteric Fermentation, Gg CH_4 yr^{-1}

$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4 $head^{-1}$ yr^{-1}

$N_{(T)}$ = the number of head of livestock species / category T in the country

T = species/category of livestock

Equation 4. IPCC Tier 1 enteric fermentation emissions equation for livestock (IPCC, 2006).

IPCC uses emission factors () based on type and number of livestock in the country to calculate Tier 1 enteric fermentation emissions. The IPCC states that population data should be sourced from national official statistics, industry sources, or if national data is unavailable, FAO data can be used (IPCC, 2006). The FAO obtains their livestock population data by surveying government agencies (FAO, 2023).

Table 1. IPCC Tier 1 enteric fermentation emission factors for dairy and non-dairy cattle. This table was adapted from the IPCC Guidelines for National GHG Inventories Table 10.11 (IPCC, 2006). This table has been adapted to only show the emission factors relevant to this study.

Tier 1 Enteric Fermentation Emission Factors for Cattle			
Regional characteristics	**Cattle Category**	**Emission Factor (kg CH4 head-1 yr-1)**	**Comments**
North America: Highly productive commercialized dairy sector feeding high quality forage and grain. Separate beef cow herd, primarily grazing with feed supplements seasonally. Fast-growing beef steer/heifers finished in feedlots on grain. Dairy cows are a small part of the population.	Dairy	128	Average milk production of 8,400 kg head-1 yr-1
	Other Cattle	53	Includes beef cows, bulls, calves, growing steers/heifers, and feedlot cattle.

$$CH_{4\ Manure} = \sum_{(T)} \frac{(EF_{(T)}\ x\ N_{(T)})}{10^6} \qquad (5)$$

Where:

$CH_{4Manure}$ = CH_4 emissions from manure management, for a defined population, Gg CH_4 yr^{-1}

$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4 $head^{-1}$ yr^{-1}

$N_{(T)}$ = the number of head of livestock species / category T in the country

T = species/category of livestock

Equation 5. IPCC Tier 1 manure methane emissions factor equation (IPCC, 2006).

To calculate Tier 1 manure methane emissions, IPCC uses the manure management methane emission factor for livestock, and the type and number of livestock in the country. Manure management emission factors used in equation 5 are derived from the IPCC and reported in Table 2.

Table 2. IPCC Tier 1 manure management emission factors by average annual temperature for livestock type in North America. This figure is adapted from Table 10.14 of the IPCC Guidelines for National GHG Inventories (IPCC, 2006). This table has been adapted to only show the emission factor relevant to this study.

Manure Management Methane Emission Factors by Temperature for Cattle, Swine, and Buffalo (kg CH_4 head^{-1} yr^{-1})																				
Regional Characteristics	**Livestock Species**	**CH_4 emission factor by average annual temperature**																		
		Cool					**Temperate**											**Warm**		
		≤ 10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**≥ 28**
North America: Liquid-based systems are commonly used for dairy cows and swine manure. Other cattle manure is usually managed as a solid and deposited on pastures or ranges.	Dairy Cows	48	50	53	55	58	63	65	68	71	74	78	81	85	89	93	98	105	110	112
	Other Cattle	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Market Swine	10	11	11	12	12	13	13	14	15	15	16	17	18	18	19	20	22	23	23
	Breeding Swine	19	20	21	22	23	24	26	27	28	29	31	32	34	35	37	39	41	44	45

IPCC derives Tier 1 emission factors from literature on measured methane emissions (Table 2, IPCC, 2006).

3.1.1.2 EPA Methane Emissions Calculations

EPA follows Tier 2 IPCC guidelines for enteric and manure methane (IPCC, 2006). Tier 2 is described by the IPCC as a more complex approach that requires country-specific data to account for regional variability in climate and management practices. The following equations are used to calculate the EPA methane emissions (IPCC, 2006):

$$DayEmit = \frac{GE\ x\ Y_m}{55.65} \quad (6)$$

Where:

DayEmit = Emission factor (kg CH_4/head/day)
GE = Gross Energy Intake (MJ/head/day)
Y_m = CH_4 conversion rate, which is the fraction of GE in feed converted to CH_4 (%)
55.65 = A factor for the energy content of methane (MJ/kg CH_4)

Equation 6. EPA Tier 2 methane emission factor equation for enteric fermentation (EPA, 2023).

EPA uses gross energy intake, the methane conversion factor based on the cattle livestock category (Equation), and 55.65—the energy content of methane— to calculate the emission factor for enteric fermentation.

$$Y_m = Y_m\,(1990)EXP\left(\frac{1.22}{(Year-1980)}\right) / \,EXP\left(\frac{1.22}{(1990-1980)}\right) \quad (7)$$

Equation 7. EPA methane conversion factor equation EPA (EPA, 2023).

The methane conversion factor (Y_m) is used to convert the gross energy in feed intake into methane emissions. Equation 5 uses the conversion factors reported in Table 2 to calculate the emission factor. The EPA used values derived from Donovan and Baldwin (1999) and the COWPOLL model to scale the Ym values specific to each region (Equation 7).

$$Emissions_{State} = DayEmit_{State}\ x\ \frac{Days}{Month}\ x\ SubPop_{State} \quad (8)$$

Where:

Emissions$_{state}$ = Emissions for state during the month (kg CH4)

DayEmit$_{state}$ = Emission factor for the subcategory and state during the month

Days/Month = Number of days in the month

SubPop$_{state}$ = Number of animals in the subcategory and state during the month

Equation 8. EPA total emissions equation (EPA, 2023).

The EPA uses Equation 8 to calculate total methane emissions by state. Total enteric fermentation methane emissions are the sum of all states for the entire year specific to livestock species.

The EPA uses the following equations to calculate tier 2 manure methane emissions (Eq. 9-12):

$$CH_4 = \sum_{State,\ Animal,\ WMS}\left(VS\ excreted_{State,\ Animal,\ WMS}\ x\ B_0\ x\ MCF\ x\ 0.662\right) \quad (9)$$

Where:

CH_4 = CH_4 emissions (kg CH_4/yr)

VS excreted State, Animal State = Amount of VS excreted in manure managed in each WMS (kg/yr)

B_0 = Maximum CH4 producing capacity (m^3 CH_4/ kg VS)

MCF = MCF for the animal group, state and WMS (%)

0.662 = the density of methane at 25° C (kg CH_4/m^3 CH_4)

Equation 9. EPA Tier 2 methane emissions for manure management (EPA, 2023).

EPA uses the quantity of volatile solids excreted in each waste management system, an assumed factor for maximum methane produced from volatile solids excretion (Eq. 10), the methane conversion factor (MCF) (Eq. 12) specific to state, animal group, and waste management system, and 0.662—the density of methane at 25º C to calculate Tier 2 manure methane emissions. EPA uses IPCC default MCF (IPCC, 2006) for dry systems (beef systems), and calculates their own MCFs (Eq. 11, Eq. 12) for anaerobic lagoons and liquid systems (dairy systems) (EPA, 2023). MCFs from 1990 to 2020 are shown in Appendix A.

$$VS\ excreted_{State,Animal,WMS} = Population_{State,Animal}\ x\ VS\ x\ WMS \qquad (10)$$

Where:

$VS\ excreted_{State,Animal,WMS}$ = Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr)

$Population_{State,Animal}$ = Annual average state animal population by animal type (head)

VS = Volatile solids production rate (kg VS/animal/year)

WMS = Distribution of manure by WMS for each animal type in a state (%)

Equation 10. EPA volatile solid excretion rate equation for cattle (EPA, 2023).

$$f = \exp[\frac{E(T_2 - T_1)}{RT_1T_2}] \qquad (11)$$

Where:

f = van't Hoff-Arrhenius f factor, the proportion of VS that are biologically available for each conversion to CH4 based on the temperature of the system

T1 = 303.15K

T2 = Ambient temperature (K) for climate zone (in this case, a weighted value for each state)

E = Activation energy constant (15,175 cal/mol)

R = Ideal gas constant (1.987 cal/K mol)

Equation 11. van't Hoff-Arrhenius factor equation used by the EPA to calculate MCF's for anaerobic lagoons and liquid systems (Safley and Westerman, 1990).

The van't Hoff-Arrhenius factor is used to calculate the proportion of volatile solids that are biologically available for conversion to methane based on the temperature of the system. To do so, the EPA uses 301.15K–T_1, the ambient temperature specific to each state–T_2, the activation energy constant and the ideal gas constant to calculate the van't Hoff-Arrhenius factor.

$$MCF_{annual} = \frac{CH_4\ generated_{annual}}{VS\ produced_{annual}\ x\ B_0} \quad (12)$$

Where:

MCF_{annual} = Methane conversion factor

VS $produced_{annual}$ = Volatile solids excreted annually

B_0 = Maximum CH_4 producing potential of the waste

Equation 12. Methane conversion factor equation used by the EPA (EPA, 2023).

EPA uses the methane generated annually, the volatile solids excreted annually and the maximum methane producing potential of the waste to calculate the MCF which is used in equation 9.

3.1.2 GWP calculations*

The data obtained from FAO and EPA were analyzed in Excel. GWP* was calculated using the equation developed by Smith et al. (2021):

$$E^{*}(t) = 4.53 \, x \, E_{100}(t) - 4.25 \, x \, E_{100}(t-20) \qquad (13)$$

Where:

E_{100} = CO_2–equivalent emissions calculated using GWP_{100}
t = current emissions
t-20 = emissions 20 years prior to current emissions
4.53 = weighting factors derived from (Smith et al. 2021)
4.25 = weighting factors derived from (Smith et al. 2021)

The GWP* using FAO beef and dairy methane emissions (FAO beef and FAO dairy, respectively) were calculated using the enteric and manure methane emissions from FAO (FAO, 2023). The GWP* for EPA beef and dairy (EPA beef and EPA dairy) were calculated using the enteric and manure methane emissions from the EPA (EPA, 2023). Enteric and manure methane emissions were summed to give a total methane emissions value which was used as the current emission rate for methane (t) and the emission rate for (t-20). To calculate the GWP* for EPA beef and dairy from 1990-2009, FAO total methane emissions for (t-20) were used given that the EPA data available started in 1990, because the EPA emissions data were not available for that time period.

3.1.3 GWP100 calculations

GWP_{100} was calculated using the equation developed by the IPCC (IPCC, 1992):

$$GWP_{100}. = (kt\ of\ gas)\ x\ (GWP)\ x\ (\frac{1\ MMT}{1000\ kt}) \qquad (14)$$

Where:

GWP_{100} = 100-year global warming potential

The GWP_{100} for FAO beef and dairy was calculated using enteric and manure methane emissions from FAOSTAT (FAO, 2023). The GWP_{100} for EPA beef and dairy was calculated using the enteric and manure methane emissions from the EPA GHG Emissions and Sinks Report (EPA, 2023). The 100-year global warming potential used for methane was twenty-eight (IPCC, 2014).

3.1.4 Beck et al. (2022) adjustments

Beck et al. (2022) used only enteric methane emissions to calculate GWP* and GWP_{100} for the FAO and EPA datasets. To compare their data with the results of this study, their data was adjusted by adding manure methane emissions to both metrics. Beck et al. (2022) used total enteric methane emissions from the FAO dataset. The FAO dataset includes emissions from farm to gate. The total methane emissions reported by the FAO includes all livestock. The EPA dataset includes emissions from farm to gate. Total emissions in the EPA dataset include beef and dairy cattle, buffalo, sheep, goats, swine, horses, mules, and asses (EPA, 2023). For both FAO and EPA dataset, beef and dairy methane emissions were added together to compare with Beck et al. (2022) total enteric methane emissions with the manure emissions adjustments.

Table 3. FAO and EPA cattle population

	FAO[1]	EPA[2]		
	Population (head)	Population (head)		
Year	Cattle[3]	Beef Cow	Dairy Cow	Beef and Dairy Cow
1990	95,816,000	81,576,000	19,513,000	101,089,000
1991	96,393,000	81,733,000	19,412,000	101,145,000
1992	97,556,000	84,272,000	19,077,000	103,349,000
1993	99,175,900	85,522,000	18,991,000	104,513,000
1994	100,973,600	87,832,000	18,714,000	106,546,000
1995	102,785,200	90,361,000	18,681,000	109,042,000
1996	103,548,200	89,593,000	18,555,000	108,148,000
1997	101,655,700	87,341,000	18,367,000	105,708,000
1998	99,744,000	86,128,000	18,137,000	104,265,000
1999	99,115,000	86,185,000	18,072,000	104,257,000
2000	98,199,000	84,810,000	18,142,000	102,952,000
2001	97,297,500	84,236,000	17,927,000	102,163,000
2002	96,723,000	84,259,000	17,833,000	102,092,000
2003	96,100,000	83,360,000	17,920,000	101,280,000
2004	94,888,000	81,673,000	17,643,000	99,316,000
2005	95,018,000	82,192,000	17,794,000	99,986,000
2006	96,701,504	83,264,000	18,078,000	101,342,000
2007	96,573,000	82,799,000	18,190,000	100,989,000
2008	96,034,500	81,532,000	18,423,000	99,955,000
2009	94,721,000	80,994,000	18,561,000	99,555,000
2010	94,081,200	80,484,000	18,298,000	98,782,000
2011	92,887,400	78,937,000	18,442,000	97,379,000
2012	91,160,200	76,858,000	18,587,000	95,445,000
2013	90,095,200	76,009,000	18,504,000	94,513,000
2014	88,526,000	74,966,000	18,517,000	93,483,000
2015	89,143,000	76,149,000	18,813,000	94,962,000
2016	91,888,000	79,322,000	18,857,000	98,179,000
2017	93,624,600	81,386,000	18,924,000	100,310,000
2018	94,298,000	81,721,000	19,006,000	100,727,000
2019	94,804,701	81,699,000	18,882,000	100,581,000
2020	93,793,300	80,813,000	18,805,000	99,618,000

[1] FAO. Crops and livestock products. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/QCL. Data of Access: 06/13/2023."

[2] EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430 R-23-002.

[3]The FAO cattle population is not disaggregated and consists of dairy and non-dairy cattle (i.e., beef).

4 RESULTS AND DISCUSSION

4.1.1 Enteric and Manure Methane Emissions

Enteric (Figure 1) and manure (Figure 2) methane emissions for both FAO and EPA varied from 1990–2020, except for EPA dairy manure methane emissions which increased every year. For both enteric and manure methane, EPA beef and dairy emissions were greater than FAO due to larger population estimates in the EPA database (Table 3).

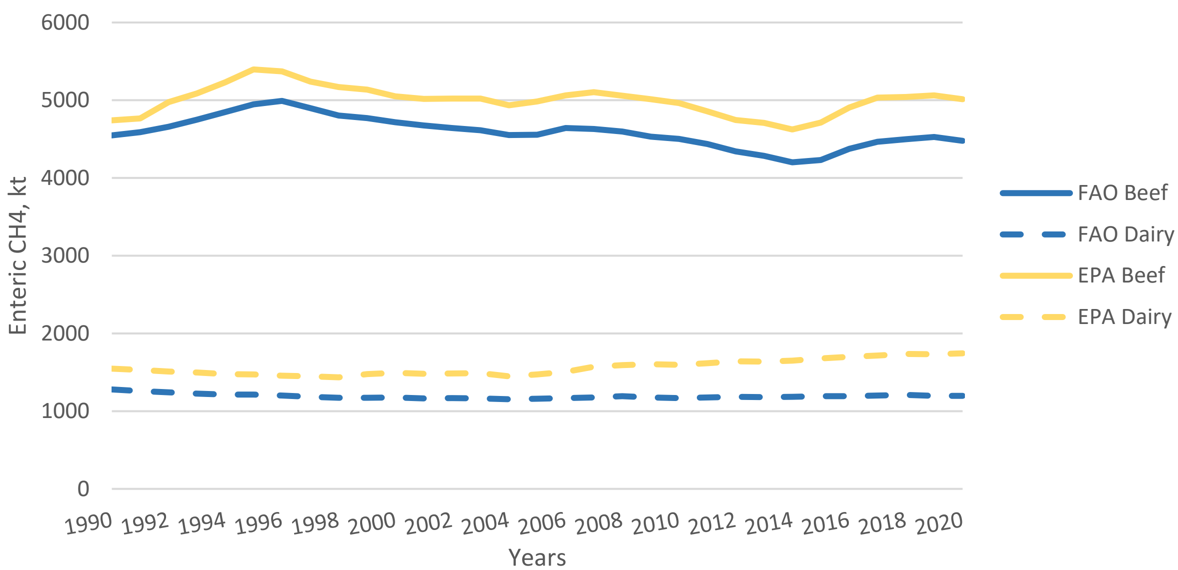

Figure 1. Total enteric methane emissions from 1990-2020 expressed in kilotons (kt) for U.S. beef and dairy systems. Data obtained from FAO are represented by the blue lines (FAO, 2023), and from EPA (EPA, 2023) are represented by the yellow lines.

Beef FAO and EPA enteric methane emissions varied from 1990–2020 (4590 ± 192 kt of methane, and 5001 ± 182 kt of methane, respectively). Dairy FAO and EPA enteric methane emissions varied as well from 1990–2020 (1191 ± 28 kt of methane, and 1563 ± 98 kt of methane, respectively). The average beef and dairy enteric methane emissions for the EPA database were greater than FAO by 9% and 31%, respectively.

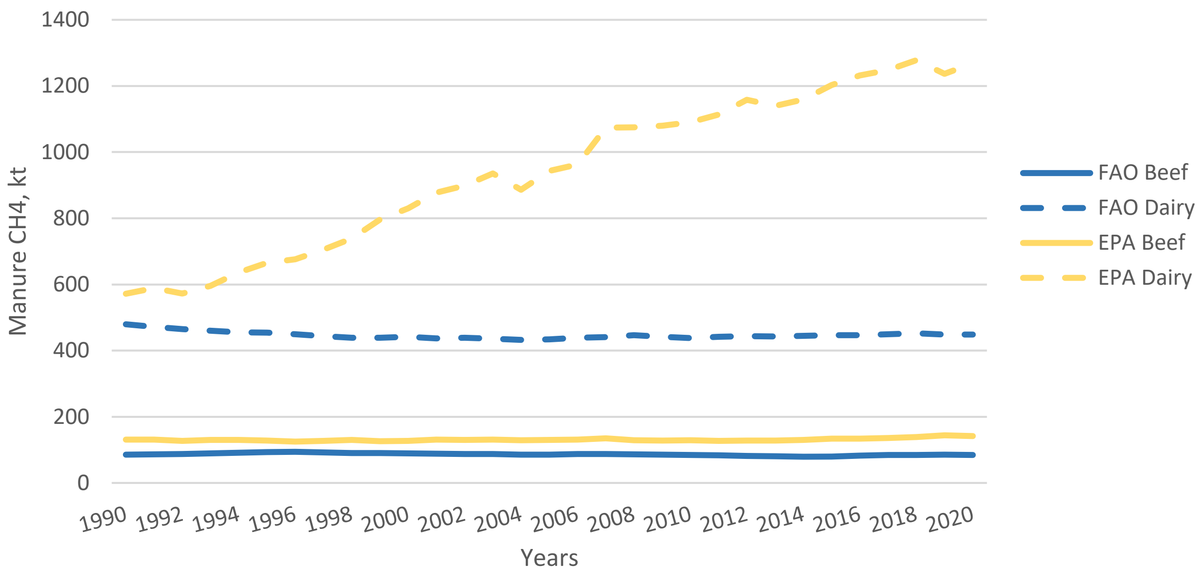

Figure 2. Total manure methane emissions from 1990-2020 expressed in kilotons (kt) for U.S. beef and dairy systems. Data obtained from FAO (FAO, 2023) are represented by the blue lines, and from EPA (EPA, 2023) are represented by the yellow lines.

Beef manure methane emissions varied from 1990-2020 (87 ± 4 kt of methane, and 131 ± 4 kt of methane, respectively). The FAO dairy manure methane emissions varied from 1990–2020 (447 ± 11 kt of methane), while the EPA dairy manure methane emissions increase by 110% from 1990–2020 because the emissions factors used by the EPA increased annually. The average beef and dairy manure methane emissions for the EPA database were greater than FAO by 51% and 111%, respectively.

4.1.2 GWP and GWP_{100} of U.S. Beef Systems*

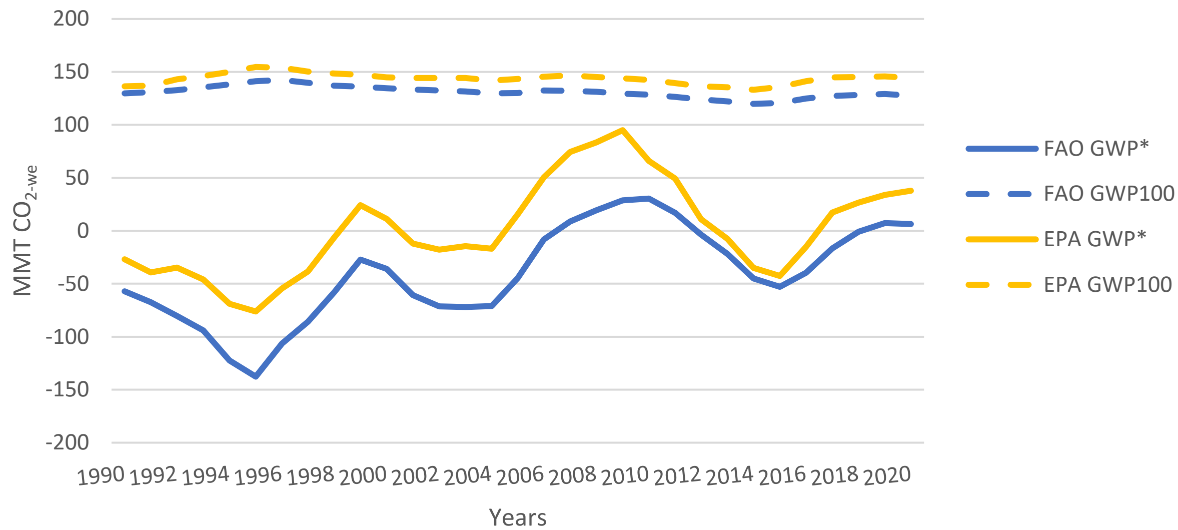

Figure 3. Annual GWP* and GWP_{100} expressed in million metric tons of CO_2 warming equivalents (MMT CO_{2-we}) from 1990–2020 for U.S. beef systems using the FAO (FAO, 2022) and EPA (EPA, 2023) databases. FAO data are shown in blue. EPA data are shown in yellow. Solid lines represent GWP*. Dashed lines represent GWP100.

For U.S. beef systems the GWP_{100} using both FAO and EPA data was greater than the GWP* (Figure 3). GWP* increases when the current emissions multiplied by 4.53 are greater than emissions from 20 years prior multiplied by 4.25 and decreases when the current methane emissions multiplied by the 4.53 factor are lower than those of 20 years prior multiplied by 4.25 (Table 4, Table 5). When GWP* increases, the difference between the weighted emissions for that year and weighted emissions from 20 years prior is positive, and when GWP* decreases, the difference between current and 20 years prior is negative (Table 4, Table 5). As a result, the beef GWP_{100} is consistently greater than the beef GWP* because the total methane emissions in any given year are greater than the difference between the emissions for that year and the emissions from 20 years prior.

Beef GWP* calculated with both FAO and EPA data increased by 111% and 241%, respectively, from 1990–2020. Average beef GWP* calculated with EPA data was 104% greater than the average beef GWP* calculated with FAO data. Greater enteric and manure methane values in the EPA data resulted in greater GWP* values using that database than the FAO database. The methane emissions from the EPA are greater than FAO because the EPA has larger cattle population values than FAO (Table 3), which are not disaggregated by livestock type. Beef GWP* was also highly variable: -40.7 ± 44.2 MMT CO_{2-we} and 1.4 ± 44.1 MMT CO_{2-we}, for FAO and EPA, respectively. Consistent with GWP*, GWP_{100} for FAO and EPA were similar, though the average GWP_{100} using the EPA data was 9.7% greater than the GWP_{100} using the FAO data (Figure 3). Both were also less variable than GWP* (130.9 ± 5.5 MMT CO_{2-we} and 143.7 ± 5.1 MMT CO_{2-we}, respectively).

Table 4. FAO GWP* for U.S. beef and dairy systems from 1990–2020

	FAO[1]							
	Beef kt CH_4				Dairy kt CH_4			
Year	Current (t)[2]	t-20[3]	Δ[4]	GWP*	Current (t)	t-20	Δ	GWP*
1990	20,994	23,035	-2,041	-57	7,967	8,976	-1,009	-28
1991	21,176	23,579	-2,403	-67	7,834	8,856	-1,021	-29
1992	21,494	24,364	-2,870	-80	7,724	8,752	-1,028	-29
1993	21,917	25,274	-3,357	-94	7,639	8,537	-898	-25
1994	22,378	26,750	-4,372	-122	7,569	8,400	-831	-23
1995	22,828	27,744	-4,916	-138	7,547	8,332	-785	-22
1996	23,037	26,840	-3,802	-106	7,472	8,252	-780	-22
1997	22,604	25,673	-3,069	-86	7,376	8,187	-810	-23
1998	22,161	24,229	-2,068	-58	7,296	8,081	-785	-22
1999	22,007	22,980	973	-27	7,298	8,029	-732	-20
2000	21,771	23,052	-1,280	-36	7,334	8,078	-743	-21
2001	21,574	23,742	-2,168	-61	7,258	8,152	-894	-25
2002	21,425	23,967	-2,543	-71	7,286	8,236	-950	-27
2003	21,287	23,855	-2,568	-72	7,240	8,272	-1,032	-29
2004	21,007	23,539	-2,532	-71	7,183	8,073	-890	-25
2005	21,029	22,629	-1,599	-45	7,215	8,214	-998	-28
2006	21,420	21,712	-292	-8	7,285	8,058	-773	-22
2007	21,376	21,066	310	9	7,326	7,725	-398	-11
2008	21,214	20,517	697	20	7,426	7,648	-222	-6
2009	20,920	19,896	1,023	29	7,337	7,514	-178	-5
2010	20,782	19,696	1,086	30	7,274	7,475	-201	-6
2011	20,472	19,867	605	17	7,334	7,350	-16	0
2012	20,040	20,166	-126	-4	7,364	7,247	118	3
2013	19,783	20,562	-779	-22	7,354	7,167	188	5
2014	19,391	20,995	-1,604	-45	7,380	7,102	279	8
2015	19,530	21,417	-1,887	-53	7,420	7,081	340	10
2016	20,200	21,613	-1,414	-40	7,425	7,010	414	12
2017	20,611	21,207	-596	-17	7,469	6,920	549	15
2018	20,760	20,791	-31	-1	7,520	6,845	675	19
2019	20,903	20,646	257	7	7,457	6,846	611	17
2020	20,658	20,426	233	7	7,449	6,881	568	16

[1]FAO. Emissions from enteric fermentation. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GE. Data of Access: 06/13/2023. FAO. Emissions from manure management. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GM. Data of Access: 06/13/2023.

[2]The emissions for said year are referred to as current emissions, they were multiplied by the weighting factor of 4.53.

[3]The emissions from 20 years prior to said year are referred to as (t-20), and they were multiplied by the weighting factor of 4.25.

[4]The delta is the difference between the current emissions multiplied by the weighting factor, and the emissions from (t-20) multiplied by the weighting factor.

Table 5. EPA GWP* for U.S. beef and dairy systems from 1990-2020

	EPA[1]							
	Beef kt CH_4				Dairy kt CH_4			
Year	Current (t)[2]	t-20[3]	Δ[4]	GWP*	Current (t)	t-20	Δ	GWP*
1990	22,075	23,035	-960	-27	9,599	8,976	623	17
1991	22,179	23,579	-1,400	-39	9,608	8,856	753	21
1992	23,121	24,364	-1,243	-35	9,441	8,752	689	19
1993	23,638	25,274	-1,636	-46	9,490	8,537	953	27
1994	24,285	26,750	-2,465	-69	9,563	8,400	1,163	33
1995	25,024	27,744	-2,720	-76	9,676	8,332	1,344	38
1996	24,901	26,840	-1,938	-54	9,658	8,252	1,406	39
1997	24,303	25,673	-1,370	-38	9,758	8,187	1,571	44
1998	24,004	24,229	-224	-6	9,848	8,081	1,768	49
1999	23,846	22,980	866	24	10,288	8,029	2,259	63
2000	23,452	23,052	400	11	10,519	8,078	2,441	68
2001	23,316	23,742	-427	-12	10,686	8,152	2,535	71
2002	23,330	23,967	-638	-18	10,800	8,236	2,563	72
2003	23,334	23,855	-521	-15	10,994	8,272	2,722	76
2004	22,940	23,539	-599	-17	10,573	8,073	2,500	70
2005	23,175	22,629	547	15	10,944	8,214	2,731	76
2006	23,520	21,712	1,808	51	11,185	8,058	3,126	88
2007	23,728	21,066	2,662	75	11,982	7,725	4,257	119
2008	23,497	20,517	2,980	83	12,082	7,648	4,434	124
2009	23,289	19,896	3,392	95	12,168	7,514	4,653	130
2010	23,067	20,710	2,357	66	12,163	9,006	3,157	88
2011	22,573	20,808	1,765	49	12,367	9,014	3,353	94
2012	22,079	21,692	387	11	12,679	8,857	3,822	107
2013	21,903	22,177	-274	-8	12,589	8,904	3,685	103
2014	21,536	22,784	-1,249	-35	12,729	8,972	3,758	105
2015	21,952	23,477	-1,525	-43	13,055	9,078	3,977	111
2016	22,827	23,362	-536	-15	13,282	9,061	4,221	118
2017	23,416	22,801	614	17	13,422	9,155	4,268	120
2018	23,470	22,521	949	27	13,658	9,240	4,418	124
2019	23,583	22,372	1,211	34	13,450	9,652	3,798	106
2020	23,352	22,002	1,350	38	13,649	9,869	3,780	106

[1]EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430 R-23-002.

[2]The emissions for said year are referred to as current emissions, they were multiplied by the weighting factor of 4.53.

[3]The emissions from 20 years prior to said year are referred to as (t-20), and they were multiplied by the weighting factor of 4.25.

[4]The delta is the difference between the current emissions multiplied by the weighting factor, and the emissions from (t-20) multiplied by the weighting factor.

4.1.3 GWP and GWP_{100} of U.S. Dairy Systems*

The GWP_{100} of U.S. dairy using the FAO data was greater than GWP*, consistent with the U.S. beef systems findings. The GWP_{100} for EPA dairy on the other hand was greater than GWP* for EPA dairy until 2000, after which point GWP* increases annually and eventually surpasses the GWP_{100} of EPA dairy (Figure 4). The GWP* of EPA dairy increases yearly because the EPA uses U.S. implied emission factors, which increase due to trends in the dairy industry towards larger farm sizes, which in turn would manage more liquid manure and produce more methane emissions (EPA, 2023). This direct relation between EPA GWP* and the implied emissions factors can be seen by the correlation between them ($R^2 = 0.96$). Not only are the emissions factors increasing annually, but the difference between weighted emissions from that year and the weighted emissions from 20 years prior surpass the current emissions used in GWP_{100}.

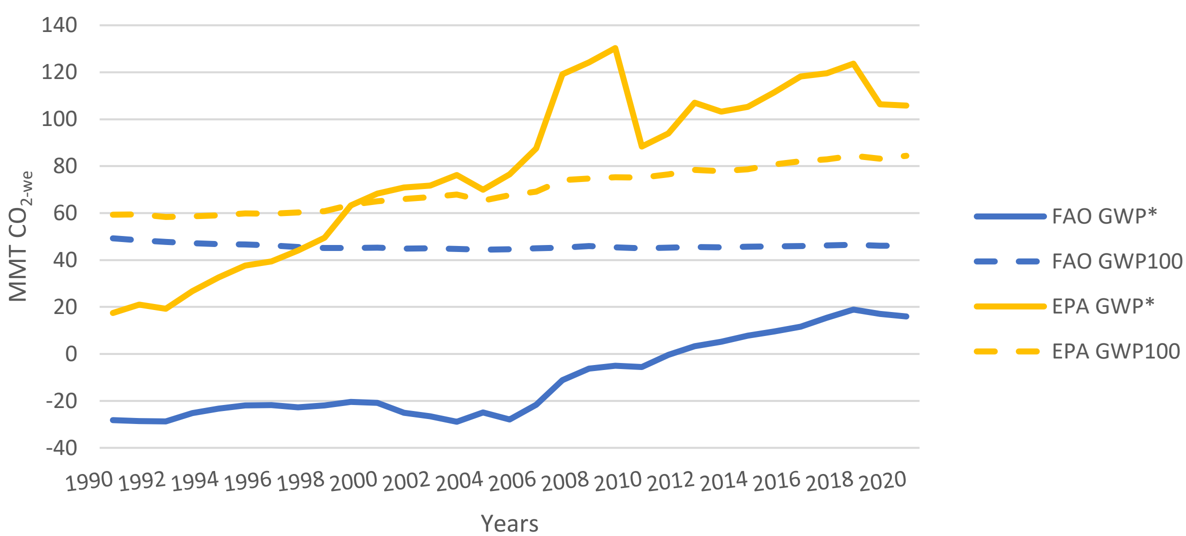

Figure 4. Annual GWP* and GWP_{100} expressed in million metric tons of CO_2 warming equivalent (MMT CO_{2-we}) from 1990–2020 for U.S. dairy systems using the FAO (FAO, 2022) and EPA (EPA, 2023) databases. FAO data are shown in blue. EPA data are shown in yellow. Solid lines represent GWP*. Dashed lines represent GWP100.

The average GWP* of EPA dairy was 609% greater than the average GWP* value of FAO dairy. GWP* values of FAO dairy were moderately variable (-11.0 ± 16.4 MMT $CO_{2\text{–we}}$) while the GWP* of EPA dairy were highly variable (78.3 ± 34.9 MMT CO_2–we). The GWP_{100} values of EPA are greater than the GWP_{100} values of FAO due to total methane emissions from the EPA being greater than total methane emissions from the FAO. Both increase annually which is a result of the yearly increase in methane emissions (Figure 1, Figure 2).

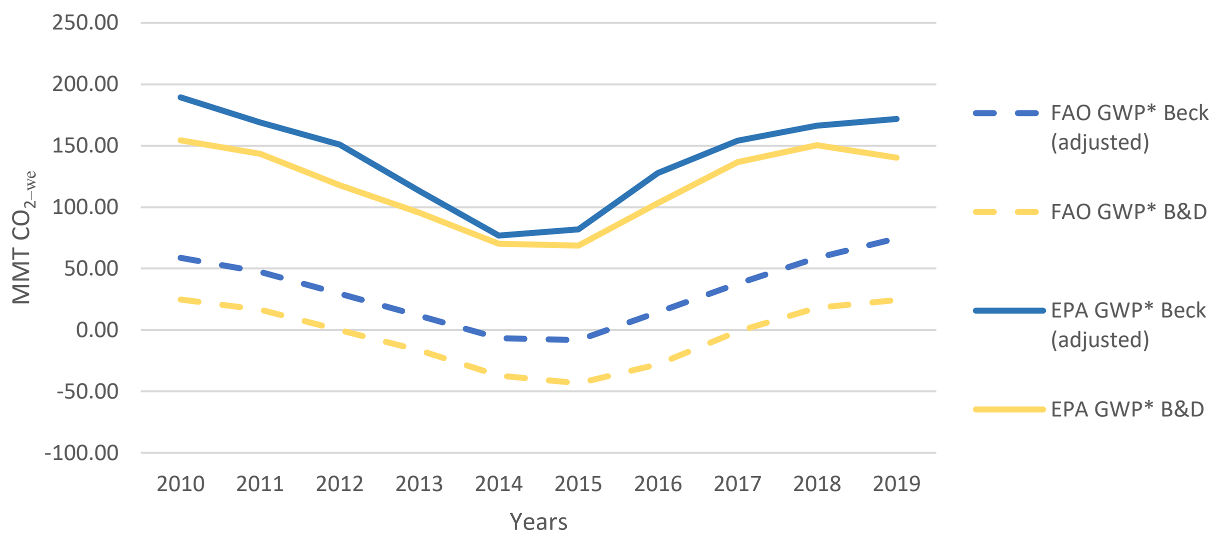

Figure 5. Comparison of annual GWP* from this study with that reported by Beck et al. (2022) from 2010–2019. Results from Beck et al. (2022) have been adjusted for manure management emissions using data from EPA (EPA, 2023) and FAO (FAO, 2022) datasets. Solid lines represent the EPA dataset and dashed lines represent the FAO dataset. Manure-adjusted GWP* from the Beck et al. (2022) study is in blue, while results from this study are shown in yellow. B&D stands = beef and dairy systems.

The results from this study for FAO agree with the findings of Liu et al. (2021) for the years 2010–2015. Based on the GWP* values being lower, the authors concluded that beef and dairy GWP* did not contribute additional climate warming during those years (Figure 5). In order to compare results from this study with a recent evaluation of GWP* from 2010-2019

(Beck et al., 2022), emissions data from that paper were adjusted to include manure emissions from beef and dairy cattle (Table 5, Table 6).

Table 6. Original and manure-adjusted[1] GWP* values for the earlier Beck et al. (2022)[2].

	FAO[3]			EPA[4]		
	Original	Adjusted	Δ (%)[5]	Original	Adjusted	Δ (%)
Year	MMT $CO_{2\text{–}we}$			MMT $CO_{2\text{–}we}$		
2010	36.13	58.83	63	87.42	189.37	117
2011	26.59	47.26	78	74.04	168.94	128
2012	9.26	29.50	219	40.28	150.85	275
2013	-7.00	11.61	66	22.39	113.08	405
2014	-27.26	-6.65	76	1.04	76.85	7,289
2015	-32.42	-8.27	74	-5.98	81.79	1,268
2016	-16.04	14.45	10	27.00	127.69	373
2017	9.19	37.54	308	61.08	153.99	152
2018	27.83	58.83	111	80.92	166.19	105
2019	35.97	74.51	107	83.13	171.83	107

[1]GWP* was adjusted by adding manure methane emissions from the FAO and EPA dataset.
[2]Beck, M. R., Thompson, L. R., Campbell, T. N., Stackhouse-Lawson, K. A. & Archibeque, S. L. Implied climate warming contributions of enteric methane emissions are dependent on the estimate source and accounting methodology. Applied Animal Science 38, 639–647 (2022).
[3] FAO. Emissions from enteric fermentation. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GE. Data of Access: 06/13/2023.
FAO. Emissions from manure management. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GM. Data of Access: 06/13/2023.
[4]EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430 R-23-002.
[5]The percent change was calculated by subtracting the adjusted and the original value, dividing it by the original value and then multiplying it by 100.

Adjusting the total methane emissions values from the Beck et al. (2022) paper to include manure methane resulted in a 10–308% increase in the GWP* values of FAO and a 105–7,289% increase in the GWP* values of EPA (Table 6). Adjusting the total methane emissions values from the Beck et al. (2022) paper to include manure methane emissions resulted in a 22–25% increase in the GWP_{100} values of FAO, and a 32–35% increase in the GWP_{100} values of EPA (Table 7). The adjusted GWP* and GWP_{100} for FAO and EPA are larger than the non-adjusted values because the addition of manure emissions increased total methane emissions by 2310 kt on average.

Table 7. Original and manure-adjusted[1] GWP_{100} values for the earlier Beck et al. (2022)[2] study.

	FAO[3]			EPA[4]		
	Original	Adjusted4	Δ (%)5	Original	Adjusted	Δ (%)
Year	MMT CO_2 eq.			MMT CO_2 eq.		
2010	168.24	205.97	22	192.36	253.88	32
2011	166.73	204.97	23	189.64	251.44	33
2012	164.22	202.44	23	187.21	251.02	34
2013	162.54	200.28	23	185.78	247.02	33
2014	160.38	199.06	24	184.32	245.14	33
2015	161.47	200.55	24	186.90	251.75	35
2016	165.79	205.64	24	192.92	259.70	35
2017	168.57	209.22	24	196.90	263.96	34
2018	169.82	211.18	24	199.33	268.41	35
2019	170.58	212.80	25	199.98	269.84	35

[1]GWP* was adjusted by adding manure methane emissions from the FAO and EPA dataset.
[2]Beck, M. R., Thompson, L. R., Campbell, T. N., Stackhouse-Lawson, K. A. & Archibeque, S. L. Implied climate warming contributions of enteric methane emissions are dependent on the estimate source and accounting methodology. Applied Animal Science 38, 639–647 (2022).
[3] FAO. Emissions from enteric fermentation. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GE. Data of Access: 06/13/2023.
FAO. Emissions from manure management. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GM. Data of Access: 06/13/2023.
[4]EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430 R-23-002.
[5]The percent change was calculated by subtracting the adjusted and the original value, dividing it by the original value and then multiplying it by 100.

Results for both livestock types, databases, and metrics from this study were comparable with those results once the adjustments were made for manure emissions (Figure 5, Figure 6). As a result of using total livestock methane emissions, manure adjusted-GWP* for the Beck et al. (2022) study was greater than the beef and dairy GWP* (Figure 5), from this study, which only used beef and dairy emissions.

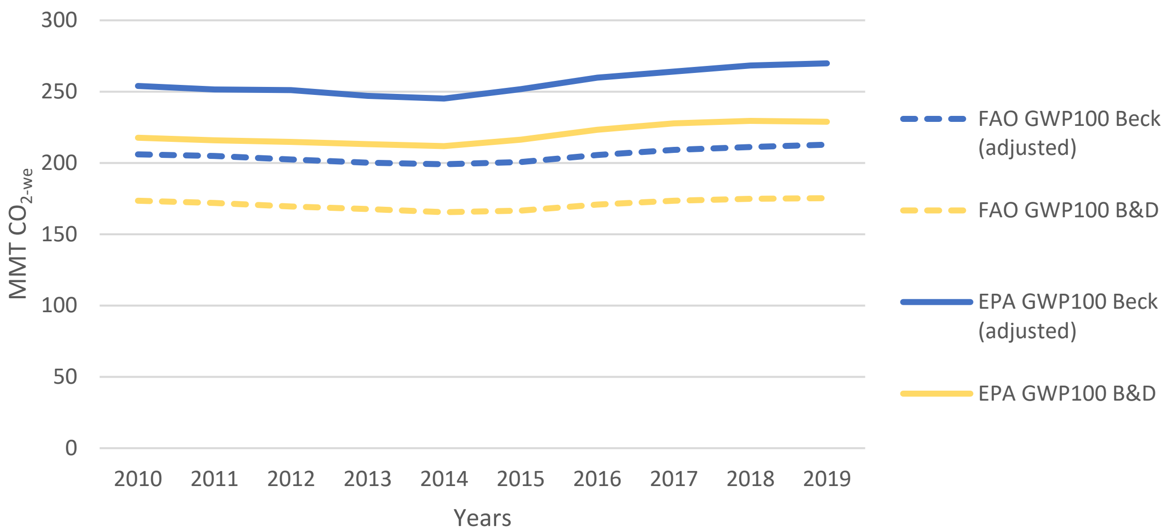

Figure 6. Comparison of annual GWP_{100} from this study with those reported by Beck et al. (2022) from 2010–2019. Results from Beck et al. (2022) have been adjusted for manure management emissions using data from EPA (EPA, 2023) and FAO (FAO, 2022) datasets. Solid lines represent the EPA dataset and dashed lines represent the FAO dataset. Manure-adjusted GWP_{100} from the Beck et al. (2022) study is in blue, while results from this study are shown in yellow. B&D = beef and dairy systems.

Consistent with manure adjusted–GWP*, the manure adjusted–GWP_{100} values from the Beck et al. (2022) study are greater than the beef and dairy GWP_{100} values (Figure 6), due to the use of total livestock emissions from both EPA and FAO databases.

*4.1.4 Real World Implications of GWP**

Based on the results, GWP* yielded lower results than GWP for both FAO and EPA beef and dairy systems except for the dairy GWP* for EPA. For most years the beef and dairy GWP* for FAO and EPA were negative. These negative values can be interpreted as a cooling effect, as mentioned in a study conducted by Liu et al. (2021), or no additional warming. The interpretation of the negative values should be taken with caution because explaining the negative values as a cooling effect, negates the warming emissions that have occurred before. Therefore, a more accurate interpretation would be that no additional warming has occurred.

The variability in GWP* results provide a challenge when it comes to possible mitigation strategies used by policy makers. The data show that GWP* increases when the current weighted emissions surpass the weighted emissions from 20 years prior, while it decreases when the weighted emissions from 20 years prior surpass the current weighted emissions. Therefore, the most important takeaway shown by GWP* is that emissions going forward must not exceed emissions from previous years in order for the GWP* to decrease. The IPCC's published work creates guidelines for countries to use in order to reduce the rate of warming. The standard metric used for these mitigation strategies is GWP. If used as the standard metric instead of GWP, GWP* could potentially penalize developing nations and/or emerging industries because their emissions will continue to grow from their baseline, causing the GWP* to increase.

5 Conclusion

The results of this study show that generally, GWP* yields lower results than GWP_{100}, but is not always the case, as demonstrated by the GWP* of EPA dairy. The use of EPA methane emissions data resulted in greater GWP* and GWP_{100} values for both beef and dairy compared to FAO emissions data, which reflects the larger population values used by the EPA and the annual increase in emissions factors. The trends observed for the GWP* and GWP_{100} of U.S. beef were consistent across the FAO and EPA datasets. However, notable differences were observed for the GWP* and GWP_{100} of U.S. dairy. For both dairy datasets, GWP* increased annually, with the GWP* of EPA increasing by 507% from 1990 to 2020. The GWP* of EPA dairy was greater than GWP* of EPA beef, despite EPA beef methane emissions being greater than dairy, because the difference between the weighted emissions of that year and the weighted emissions from 20 years prior for dairy are higher than for beef. It is important to note that accounting methods play a key role in the amount of methane emissions that are calculated, and thus how GWP_{100} and GWP* are calculated. Data source is critical to the policy implications of GWP* and GWP_{100} for livestock systems, as demonstrated by a 609% difference between the average dairy EPA GWP* (78.3 ± 34.9 MMT $CO_{2\text{-we}}$) and dairy FAO GWP* (-11 ± 16.43 MMT $CO_{2\text{-we}}$) values. In addition, the EPA emission factor used to calculate manure methane emissions for EPA increases yearly, which contributes significantly to the GWP* estimate based on EPA data and may be a source of error depending on the assumptions in the equations. GWP* demonstrates that its method of accounting for SLCPs can yield lower results than GWP_{100} but is subjective to data sourcing. Thus, methane can have a positive or negative effect on global warming which can be interpreted as additional warming or no additional warming impact.

References

Allen, M. R., K. P. Shine, J. S. Fuglestvedt, R. J. Millar, M. Cain, D. J. Frame, and A. H. Macey. 2018. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. npj Clim Atmos Sci. 1:16. doi:10.1038/s41612-018-0026-8.

Allen, M. R., G. P. Peters, K. P. Shine, C. Azar, P. Balcombe, O. Boucher, M. Cain, P. Ciais, W. Collins, P. M. Forster, D. J. Frame, P. Friedlingstein, C. Fyson, T. Gasser, B. Hare, S. Jenkins, S. P. Hamburg, D. J. A. Johansson, J. Lynch, A. Macey, J. Morfeldt, A. Nauels, I. Ocko, M. Oppenheimer, S. W. Pacala, R. Pierrehumbert, J. Rogelj, M. Schaeffer, C. F. Schleussner, D. Shindell, R. B. Skeie, S. M. Smith, and K. Tanaka. 2022. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Clim Atmos Sci. 5:5. doi:10.1038/s41612-021-00226-2. Available from: https://www.nature.com/articles/s41612-021-00226-2

Beck, M. R., L. R. Thompson, T. N. Campbell, K. A. Stackhouse-Lawson, and S. L. Archibeque. 2022. Implied climate warming contributions of enteric methane emissions are dependent on the estimate source and accounting methodology. Applied Animal Science. 38:639–647. doi:10.15232/aas.2022-02344.

Cain, M., J. Lynch, M. R. Allen, J. S. Fuglestvedt, D. J. Frame, and A. H. Macey. 2019. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. npj Clim Atmos Sci. 2:29. doi:10.1038/s41612-019-0086-4.

Cicerone, R. J., and R. S. Oremland. 1988. Biogeochemical aspects of atmospheric methane. Global Biogeochem. Cycles. 2:299–327. doi:10.1029/GB002i004p00299.

Del Prado, A., J. Lynch, S. Liu, B. Ridoutt, G. Pardo, and F. Mitloehner. 2023. Animal board invited review: Opportunities and challenges in using GWP* to report the impact of ruminant livestock on global temperature change. animal. 17:100790. doi:10.1016/j.animal.2023.100790. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1751731123000861

Donovan, K. and L. Baldwin. “Results of the AAMOLLY Model Runs for the Enteric Fermentation Model”; University of California, Davis, 1999.

Eshel, G., A. Shepon, T. Shaket, B. D. Cotler, S. Gilutz, D. Giddings, M. E. Raymo, and R. Milo. 2018. A model for ‘sustainable’ US beef production. Nat Ecol Evol. 2:81–85. doi:10.1038/s41559-017-0390-5.

FAO. Crops and livestock products. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/QCL. Data of Access: 06/13/2023.

FAO. Emissions from enteric fermentation. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GE. Data of Access: 06/13/2023.

FAO. Emissions from manure management. License: CC BY-NC-SA 3.0 IGO. Extracted from: https://www.fao.org/faostat/en/#data/GM. Data of Access: 06/13/2023.

Farooq, M., Rehman, Abdul, and M. Pisante. 2019. Innovations in Sustainable Agriculture. Springer International Publishing, Cham. Available from: http://link.springer.com/10.1007/978-3-030-23169-9

EPA (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430 R-23-002.

Heflin, K. R., D. B. Parker, G. W. Marek, B. W. Auvermann, and T. H. Marek. 2019. Greenhouse-gas emissions of beef finishing systems in the Southern High Plains. Agricultural Systems. 176:102674. doi:10.1016/j.agsy.2019.102674.

Henderson, A. D., A. Asselin-Balençon, M. C. Heller, J. Burek, D. Kim, L. Lessard, M. Margni, R. Saad, M. D. Matlock, G. Thoma, Y. Wang, and O. Jolliet. 2023. Spatialized Life Cycle Assessment of Fluid Milk Production and Consumption in the United States. Sustainability. 15:1890. doi:10.3390/su15031890.

IPCC, 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Keeble, B. R. 1988. The Brundtland report: 'Our common future.' Medicine and War. 4:17–25. doi:10.1080/07488008808408783.

Liu, S., J. Proudman, and F. M. Mitloehner. 2021. Rethinking methane from animal agriculture. CABI Agric Biosci. 2:22. doi:10.1186/s43170-021-00041-y.

Lynch, J., M. Cain, R. Pierrehumbert, and M. Allen. 2020. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. Environ. Res. Lett. 15:044023. doi:10.1088/1748-9326/ab6d7e.

Milich, L. 1999. The role of methane in global warming: where might mitigation strategies be focused? Global Environmental Change. 9:179–201. doi:10.1016/S0959-3780(98)00037-5.

Mitchell, J. F. B. 1989. The "Greenhouse" effect and climate change. Rev. Geophys. 27:115. doi:10.1029/RG027i001p00115.

Nieto, M., O. Barrantes, L. Privitello, and R. Reiné. 2018. Greenhouse Gas Emissions from Beef Grazing Systems in Semi-Arid Rangelands of Central Argentina. Sustainability. 10:4228. doi:10.3390/su10114228.

Patra, A. K. 2012. Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. Environ Monit Assess. 184:1929–1952. doi:10.1007/s10661-011-2090-y.

Pelletier, N., R. Pirog, and R. Rasmussen. 2010. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agricultural Systems. 103:380–389. doi:10.1016/j.agsy.2010.03.009.

Pierrehumbert, R. T. 2014. Short-Lived Climate Pollution. Annu. Rev. Earth Planet. Sci. 42:341–379. doi:10.1146/annurev-earth-060313-054843.

Place, S. E., C. J. McCabe, and F. M. Mitloehner. 2022. Symposium review: Defining a pathway to climate neutrality for US dairy cattle production. Journal of Dairy Science. 105:8558–8568. doi:10.3168/jds.2021-21413.

Ranganathan, J., D. Vennard, R. Waite, B. Lipinski, T. Searchinger, P. Dumas, A. Forslund, Herve Guyomard, Stephane Manceron, E. Marajo-Petitzon, C. L. Mouel, P. Havlik, M. Herrero, X. Zhang, S. Wirsenius, F. Ramos, Xiaoyuan Yan, M. Phillips, and Rattanawan Mungkung. 2016. Shifting Diets for a Sustainable Food Future. doi:10.13140/RG.2.1.3808.2961. Available from: http://rgdoi.net/10.13140/RG.2.1.3808.2961

Smith, M. A., M. Cain, and M. R. Allen. 2021. Further improvement of warming-equivalent emissions calculation. npj Clim Atmos Sci. 4:1–3. doi:10.1038/s41612-021-00169-8.

Smith, S. J., and T. M. L. Wigley. 2000. Global Warming Potentials: 2. Accuracy. Climatic Change. 44:459–469. doi:10.1023/A:1005537014987.

Smith, S. M., J. A. Lowe, N. H. A. Bowerman, L. K. Gohar, C. Huntingford, and M. R. Allen. 2012. Equivalence of greenhouse-gas emissions for peak temperature limits. Nature Clim Change. 2:535–538. doi:10.1038/nclimate1496.

Thoma, G., O. Jolliet, and Y. Wang. 2013a. A biophysical approach to allocation of life cycle environmental burdens for fluid milk supply chain analysis. International Dairy Journal. 31:S41–S49. doi:10.1016/j.idairyj.2012.08.012.

Thoma, G., J. Popp, D. Nutter, D. Shonnard, R. Ulrich, M. Matlock, D. S. Kim, Z. Neiderman, N. Kemper, C. East, and F. Adom. 2013b. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. International Dairy Journal. 31:S3–S14. doi:10.1016/j.idairyj.2012.08.013.

Waldrip, H. M., D. B. Parker, S. Miller, D. N. Miller, K. D. Casey, R. W. Todd, B. R. Min, M. J. Spiehs, and B. Woodbury. 2020. Nitrous Oxide from Beef Cattle Manure: Effects of Temperature, Water Addition and Manure Properties on Denitrification and Nitrification. Atmosphere. 11:1056. doi:10.3390/atmos11101056.

World Commission on Environment and Development, ed. 1987. Our common future. Oxford University Press, Oxford ; New York.

Wuebbles, D. J., and J. S. Tamaresis. 1993. The Role of Methane in the Global Environment. In: M. A. K. Khalil, editor. Atmospheric Methane: Sources, Sinks, and Role in Global Change. Springer Berlin Heidelberg, Berlin, Heidelberg. p. 469–513. Available from: http://link.springer.com/10.1007/978-3-642-84605-2_20