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SUSTAINABILITY AND INTEGRATED SYSTEMS: *Perspective and Commentary*

Implied climate warming contributions of enteric methane emissions are dependent on the estimate source and accounting methodology*

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ABSTRACT

Objective: The objective of this project was to demonstrate differences in methane (CH_4) emission estimates between 2 reporting entities and to illustrate how the contribution to climate warming of enteric CH_4 emissions is dependent on accounting methodologies.

Materials and Methods: United States enteric CH_4 emissions were accessed from the Food and Agriculture Organization (FAO) and US Environmental Protection Agency (EPA), and cattle inventory numbers were obtained from the USDA-National Agricultural Statistics Service (NASS) website and EPA spreadsheet. Enteric CH_4 emission estimates from both sources were then expressed as CO_2 equivalence (CO_2-e) and warming equivalence (CO_2-we) using both the 100-yr global warming potential (GWP100) and the newer global warming potential* (GWP*) methodologies.

Results and Discussion: Almost all of the year-to-year variability in the FAO data set was explained by NASS cow and calves inventory ($R^2 = 0.99$), whereas much less variability was explained by EPA cattle inventory for the EPA data set ($R^2 = 0.45$). The EPA estimates were consistently greater than FAO estimates, and only a small amount of variation was accounted for ($R^2 = 0.41$). Despite these differences, GWP* methodologies produced much smaller CO_2-e values compared with GWP100 for both data sets.

Implications and Applications: This work highlighted several important concepts to understand. First, it is important to understand the methodology for estimating enteric CH_4 emissions used by different reporting bodies. Second, with both the FAO and EPA data sources, GWP* methodology provides a smaller estimate of warming contribution than the GWP100 method. Finally, this evaluation also highlights how this greenhouse gas accounting method is not a panacea for this source of greenhouse gas emissions.

Key words: enteric methane, greenhouse gas, emissions inventory

INTRODUCTION

Enteric methane (CH_4) emissions are the primary greenhouse gas (**GHG**) emitted by the beef and dairy sectors (US EPA, 2021a), bringing increased societal scrutiny (Steinfeld et al., 2006). There are critical issues with accounting methodologies, including emission allocation and model selection, which cause confusion when interpreting emission data (FAO, 2016; IPCC, 2019). Originally, accounting methodologies lacked structure for livestock, which made comparisons between Life Cycle Assessments difficult. First, ISO 14040 provided standards for conducting Life Cycle Assessments providing guidance for (1) goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation. Subsequently, the Food and Agriculture Organization (**FAO**) Livestock Assessment and Performance Partnership guidelines aimed to further harmonize Life Cycle Assessments of livestock systems.

Currently, the Intergovernmental Panel on Climate Change (**IPCC**) (IPCC, 2019) recommends 3 tier approaches to calculate enteric CH_4 emissions. Tier 1 is a

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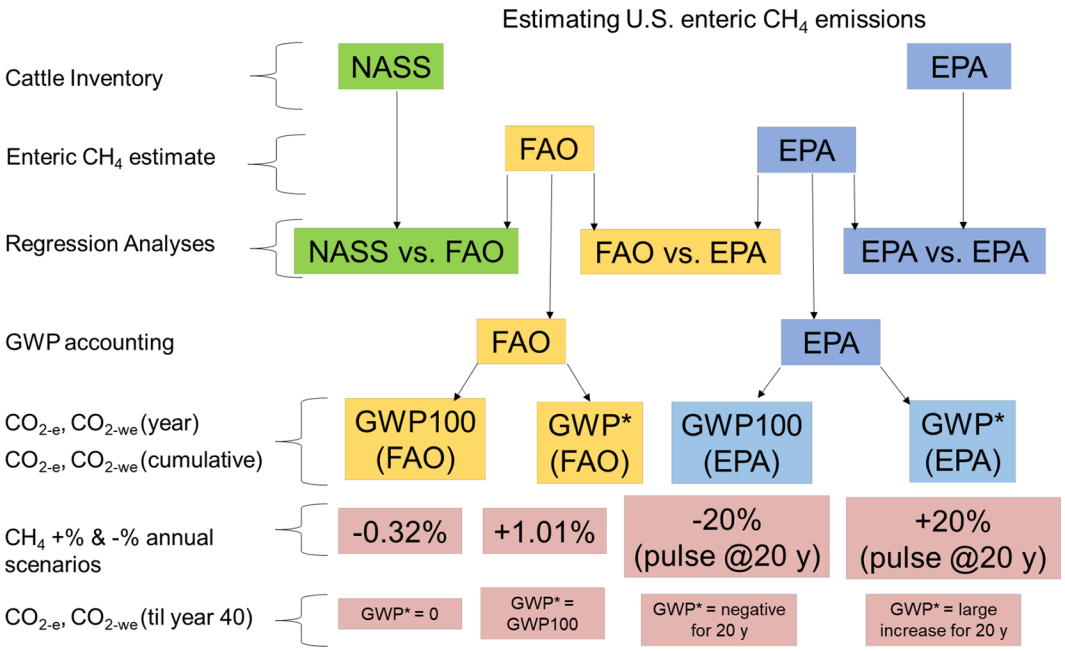


Figure 1. This figure graphically displays methods and key outcomes from this work. Boxes filled in blue represent items related to the US Environmental Protection Agency (EPA) data set, yellow represent the Food and Agriculture Organization (FAO) data set, and green represents the National Agricultural Statistics Service (NASS) cattle inventory data. The red boxes represent items related to 4 future scenarios to illustrate how these scenarios might influence future contributions of enteric methane to climate change. GWP100 = 100-yr global warming potential; GWP* = newer global warming potential*; $CO_{2\text{-}e}$ = CO_2 equivalence; and $CO_{2\text{-}we}$ = CO_2 warming equivalence.

simplistic approach that relies on default emission factors, whereas tiers 2 and 3 are of advanced complexity. The default emission factor (tier 1) uses a standard conversion factor based on GE lost as CH_4 to calculate emission, effectively making cattle population the predominate factor deciding emission inventories. Yet, as highlighted by van Lingen et al. (2019), equations that account for diet and animal characteristics provide better estimates of enteric CH_4.

Typically, emission accounting relates all GHG to CO_2 equivalence (**CO_2-e**). This conversion is done by multiplying the emissions of non-CO_2 GHG [e.g., CH_4 and nitrous oxide (N_2O)] by a factor termed the global warming potential (**GWP**). The GWP factors can vary based on the gas type and the time horizon of interest. A 100-yr time horizon was originally used as the basis for the Kyoto Protocol and since then has been predominantly used (IPCC, 1990). This method and time horizon likely work well for longer-lived climate forcers such as N_2O (114-yr lifespan in atmosphere) but are inappropriate for short-lived climate forcers (**SLCF**), such as CH_4, which has an atmospheric lifespan of only 12 yr (US EPA, 2021a; Allen et al., 2022). To account for SLCF an alternative method has been developed [the newer global warming potential* (**GWP***); Allen et al., 2018; Lynch et al., 2020; Allen et al., 2022]. The objectives of this analysis are to (1) demonstrate differences in emission estimates between 2 reporting entities (FAO and EPA) and to (2) demonstrate how the contribution to climate warming of enteric CH_4 emissions is dependent on accounting methodologies [100-yr global warming potential (**GWP100**) and GWP*).

MATERIALS AND METHODS

Figure 1 depicts key methods and outcomes obtained from this current work. The left side of Figure 1 represents actions that were taken, such as data frame acquisition of cattle inventory and CH_4 estimates, regression analysis, emission accounting methods (i.e., relating CH_4 emissions to CO_2-e or CO_2-we), and applying the accounting methodologies using different future scenarios. Detailed methodologies are in the subsequent paragraphs.

All data compiled and reported by this project are publicly available and published online by their respective reporting bodies. The FAO emission data, from here on called "FAO data," were obtained from the FAOSTAT website (FAO, 2022). This database provided enteric CH_4 emissions from all livestock species from 1961 to 2019. However, to test how the FAO data related to national inventories of cows and calves from both beef and dairy, herd inventory numbers were compiled from the USDA National Agricultural Statistics Service (**NASS**) biannual reports on cow and calves inventory in January and June (USDA-NASS, 2022). Data compiled were from 1971 until 2019. The FAO data and NASS data were regressed against each other with cow and calf inventory as the independent variable and the FAO enteric emissions as the

dependent variable. This analysis was done using the 'lm' function of base R (R Core Team, 2021; v. 4.1.0).

Data used to generate the US Environmental Protection Agency's (**US EPA**) yearly publication (US EPA, 2021a) were obtained from their publicly available website (US EPA, 2021b) and are referred to as "EPA data" from here on. The EPA does not use NASS survey data for the cattle inventory numbers that are then used to determine enteric emissions; instead they use the Cattle Enteric Fermentation Model, which was developed by the EPA (US EPA, 2021a). As such, to relate cattle inventory to enteric CH_4 emissions, we accessed the EPA data frame providing national cattle inventory data listed in Annex Table 140 (US EPA, 2021a), which is available for download (US EPA, 2021b). Linear regression was conducted using the 'lm' function of base R (R Core Team, 2021; v. 4.1.0) to determine the relationship between the EPA emission data and their cattle inventory numbers. Finally, to display how the EPA and FAO differ, these 2 sources of emission estimates were regressed as described previously.

To address the second objective of this work, demonstrating the difference between the accounting methods that are typically used (i.e., GWP100; IPCC, 2013) and a newer method (GWP*****; Lynch et al., 2020), the following calculations were applied for both the FAO and the EPA emission data sets.

The GWP100 equation to convert CH_4 emissions to CO_2-e is as follows:

$$CH_4, \text{ Mt, } CO_2 \text{ equivalence} = 28 \times CH_4 \text{ emissions, Mt.} \quad [1]$$

The equation to relate CH_4 emissions to **CO_2-we** (CO_2 warming equivalence) using the GWP* methodology is as follows:

$$CH_4, \text{ Mt, } CO_2 \text{ warming equivalence} = [r \times (\Delta CH_4/\Delta t) \times H + s \times CH_4] \times GWP_H, \quad [2]$$

where r is the weighting factor (0.75) applied to changes in CH_4 emission rates (**ΔCH_4**; Mt), s represents the weighting factor (0.25) associated with current emission rates, Δt (years) is the time horizon where current emissions are compared with previous emissions, and GWP_H is the GWP of CH_4 on an H-year basis.

When considering a 20-yr time horizon and a 100-yr basis of GWP for GWP*, which Allen et al. (2018) determined to provide a good fit for modeled warming, the equation can be simplified to

$$CH_4, \text{ Mt, } CO_2 \text{ warming equivalence} = (4 \times CH_{4(t)} - 3.75 \times CH_{4(t-20)}) \times 28, \quad [3]$$

where $CH_{4(t)}$ is the CH_4 emitted (Mt) at year t and $CH_{4(t-20)}$ is the amount of CH_4 emitted (Mt) during 20 yr before year t (Lynch et al., 2020). Recently, an additional scaling factor (g) was added to Equation [2] so that

$$CH_4, \text{ Mt, } CO_2\text{-we} = [g \times r \times (\Delta CH_4/\Delta t) \times H + g \times s \times CH_4] \times GWP_H, \quad [4]$$

where g is 1.13. This scaling factor was included because it generated CO_2-we estimates that better aligned with climate models that predict actual warming, when using more ambitious mitigation scenarios [using Representative Concentration Pathway (RCP) 2.6]. However, it was found that this additional scaling factor performed worse with higher emission scenarios (RCP 4.5 and RCP 6; Smith et al., 2021). Applying this update to Equation [3] gave the latest equation to calculate GWP* (Smith et al., 2021):

$$CH_4, \text{ Mt, } CO_2\text{-we} = (4.53 \times CH_{4(t)} - 4.25 \times CH_{4(t-20)}) \times 28. \quad [5]$$

The latest update to the GWP* methodology (Equation [5]) was used to calculate CO_2-we in this current work. All figures were generated using ggplot (Wickham, 2016) of R (R Core Team, 2021; v. 4.1.0).

RESULTS AND DISCUSSION

FAO vs. EPA Enteric CH_4 Data Sets

Figure 2 presents the enteric CH_4 estimates that were downloaded from the FAO and EPA data sets. Across all tiers of emission accounting suggested by the IPCC (2019), animal population numbers play a major role in the total estimated enteric CH_4 emissions. However, the degree that animal inventory influences these emission estimates is tier dependent. In tier 1 methodology, animal numbers are multiplied by a common emission factor. This fact can be seen in the current study, where NASS cow and calves inventory numbers almost perfectly account for the year-to-year variability in the FAO enteric CH_4 data ($R^2 = 0.99$; Figure 3). The EPA enteric CH_4 emission data uses the tier 2 approach to develop estimates. This applies a unique emission factor to specific animal classes in a regionally specific manner (US EPA, 2021a). As such, it is not surprising that the total number of cows and calves (both dairy and beef) from the EPA data set accounted for only 45% of the year-to-year variability in the EPA enteric CH_4 data ($R^2 = 0.45$; Figure 3).

By using the different accounting methodologies, the EPA and FAO report widely ranging emission estimates. The EPA estimates for enteric CH_4 emissions were larger than the FAO estimates for every year from 1990 to 2019 (Table 1). Furthermore, although there was a linear relationship ($P < 0.01$) between the 2 sources of enteric CH_4 emissions, regressing the 2 enteric methane emission data sets against each other only accounted for 41% of the year-to-year variation ($R^2 = 0.41$; Figure 4). Thus, it

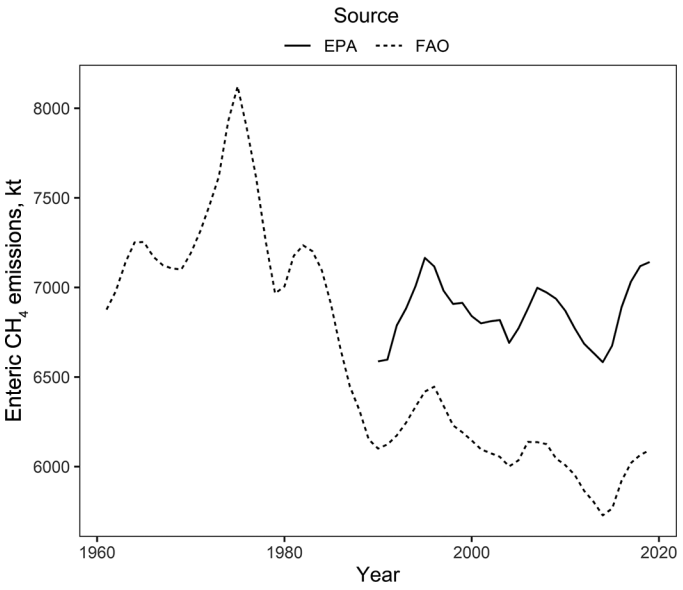


Figure 2. Annual US enteric methane (CH_4) emissions in kilotonnes for years reported by the US Environmental Protection Agency (EPA) or the Food and Agriculture Organization (FAO). The years 1961 to 2019 were available for download for the FAO data, whereas the EPA data only had data available from 1990 to 2019.

is important to understand the source of the information being cited when discussing inventories of enteric CH_4 and GHG emissions in general and to understand the different assumptions made by the specific reporting bodies when they derived these estimates. As reported by NASS, cattle populations in the United States have been declining since the 1970s, which highlights the inappropriate role that these estimates have on results from FAO (USDA-NASS, 2022). Hristov et al. (2018) highlighted that while there has been a decrease in cattle populations, BW and DMI of beef and dairy cattle have been increasing. These facts, in part, explain why only 45% of the variation in the EPA estimates is explained by population alone. Additionally, the results of Hristov et al. (2017) demonstrate the role of emission factors using a more robust, spatial gridded analysis of US livestock CH_4 emissions. Those authors reported that the most important components to enteric CH_4 estimates were DMI and methane yield per unit of DM consumed.

*GWP100 vs. GWP**

The GWP100 method for relating CH_4 emissions to CO_2-e has been widely adopted by several reporting entities, such as the IPCC, FAO, and EPA (albeit the EPA uses a CH_4 GWP100 value of 25). However, some have suggested that it does not adequately represent emissions of SLCF (like CH_4, which only lasts 12 yr in the atmosphere; US EPA, 2021a) to CO_2 in terms of CH_4 actual warming potential (Allen et al., 2022; IPCC, 2021). A newer metric for SLCF has been under development by climate scientists to more aptly model the impact of these GHG pollutants on global temperature change (Allen et al., 2018; Cain et al., 2019; Smith et al., 2021; IPCC, 2021). The

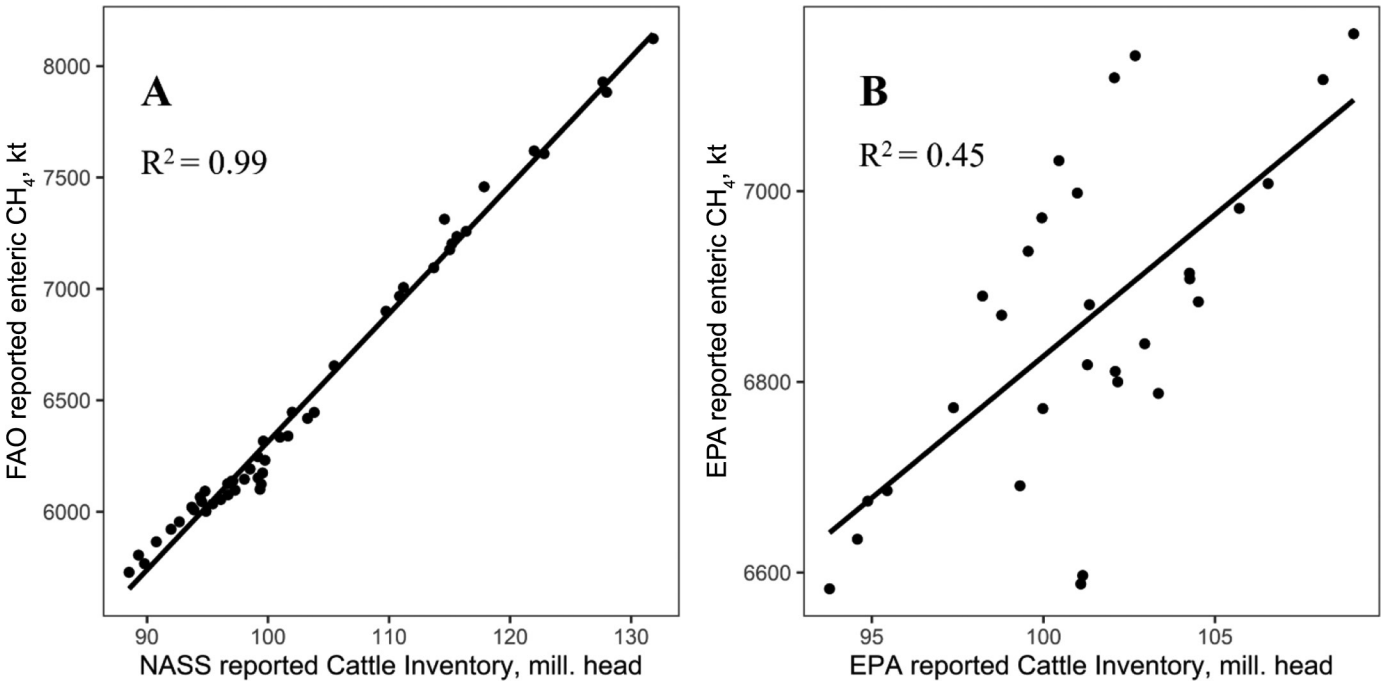


Figure 3. Food and Agriculture Organization (FAO)–reported enteric CH_4 emissions compared with National Agricultural Statistics Service (NASS)–reported cattle inventory (cows and calves) in millions (mill.) of head (A), and EPA reported enteric CH_4 emissions compared with the EPA cattle inventory numbers (dairy and beef cows and calves) derived from their Cattle Enteric Fermentation Model in millions of head (B).

Table 1. Yearly and cumulative enteric methane expressed as carbon dioxide equivalence or warming equivalence ($CO_{2\text{-}e}$ and $CO_{2\text{-}we}$, respectively; Mt) emissions calculated using the traditional GWP100 [global warming potential (GWP) = 28] method or the GWP* method, respectively[1]

	GWP100		GWP*	
Mt of $CO_{2\text{-}e}$ or $CO_{2\text{-}we}$	FAO	EPA	FAO	EPA
Yearly				
2010	168.24	192.36	36.13	87.42
2011	166.73	189.64	26.59	74.04
2012	164.22	187.21	9.26	40.28
2013	162.54	185.78	−7.00	22.39
2014	160.38	184.32	−27.26	1.04
2015	161.47	186.90	−32.42	−5.98
2016	165.79	192.92	−16.04	27.00
2017	168.57	196.90	9.19	61.08
2018	169.82	199.33	27.83	80.92
2019	170.58	199.98	35.97	83.13
Cumulative				
2010	168.24	192.36	36.13	87.42
2011	334.97	382.00	62.72	161.46
2012	499.19	569.21	71.98	201.74
2013	661.73	754.99	64.98	224.13
2014	822.12	939.32	37.72	225.17
2015	983.59	1,126.22	5.30	219.19
2016	1,149.38	1,319.14	−10.74	246.19
2017	1,317.94	1,516.03	−1.55	307.27
2018	1,487.76	1,715.36	26.28	388.20
2019	1,658.35	1,915.34	62.24	471.32

[1]GWP100 = 100-yr global warming potential; GWP* = newer global warming potential*; FAO = Food and Agriculture Organization; EPA = US Environmental Protection Agency.

developers of this method, GWP*, suggest that although it still dependent on time horizon decisions like traditional GWP accounting metrics, it better represents the impact of SLCF on future climate impacts (Cain et al., 2019; IPCC, 2021). The emission rate accounting methods, however, can result in differing results for GWP* (Table 1). It should also be noted that although new, GWP* is not the first attempt at more aptly predicting warming impact of the different GHG emissions (IPCC, 2021). In 2005, Shine et al. (2005) proposed a global temperature potential metric that uses sustained reductions rather than a pulse of CO_2 equivalent emissions, such as the GWP100, and found it performed adequately across gases of various lifetimes. Furthermore, the very use of GWP100 has been critiqued by climate scientists since its adoption, which highlights the inherent complexity that occurs at the nexus of GHG accounting and public policy (O'Neill, 2000; Shine, 2009; Cain et al., 2021).

Starting with annual emissions, FAO estimates of US enteric CH_4 emissions result in lower CO_2-we relative to EPA calculations every year from 2010 to 2019 (Figure 5). Furthermore, 4 of these years (2013–2016) all resulted in negative CO_2-we compared with only one of the years for the EPA data (2015). Comparison of cumulative emissions (2010 to 2019) for GWP100 and GWP* provides even more disparaging results between FAO and EPA (Figure 6). When using GWP* on the FAO data, the estimated CO_2-we are negative from 2013 to 2016 (Table 1 and Figure 5) and actually reaches cumulative negative warming impact for years 2016 and 2017 (Table 1 and Figure 6). When GWP* is applied to the EPA data, cumulative CO_2-we steadily increases each year and only declines in 2015. This highlights a few key points:

- For the animal science and production community, it is important to understand that although it is an improvement relative to the traditional GWP100 methodology, GWP* is only as good as model inputs.
- For sources using weak accounting methods, results, such as FAO dependent solely on animal population, should be interpreted as such, particularly for the United States and other countries with more robust accounting.
- Using GWP* is not a panacea or one that will always result in lower climate impact. This will be further demonstrated below.

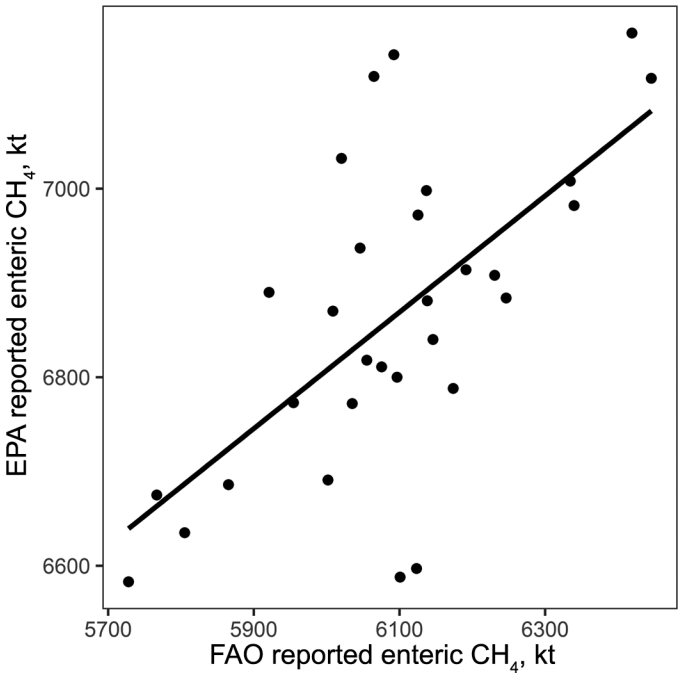


Figure 4. The relationship between the US enteric CH_4 emissions reported by the US Environmental Protection Agency (EPA) and the Food and Agriculture Organization (FAO). Regression equation: EPA CH_4 = 3,103.5 + 0.62 × FAO CH_4; R^2 = 0.41.

An Overview of GWP100 and GWP and Future Emission Scenarios*

Figure 7 illustrates how GWP100 and GWP* methods for relating CH_4 emissions to CO_2-e and CO_2-we, respectively, respond across 4 scenarios. The scenarios started at yr 1, which could be thought of as 1 × 2019 enteric CH_4 emissions, and span 43 yr to demonstrate how the 2 emission accounting methodologies respond over time. The first 2 scenarios were chosen because they demonstrate 2 important concepts about the differences between GWP100 and GWP*. In scenario 1 we assumed a 0.32% annual decrease in enteric CH_4 emissions. Intuitively, CO_2-e determined using the traditional GWP100 methods likewise would suggest a 0.32% decrease. However, using the GWP* methodology would suggest that there would be no net change in CO_2-we and subsequently no net contribution to climate warming. This means that any amount of emissions greater than 0.32% annual decrease would mean that enteric emissions were contributing to warming, whereas any additional decrease below the 0.32% decrease would actually represent a net-negative contribution to warming. This result is consistent with those presented by Cain et al. (2019).

In scenario 2 there was a 1.01% assumed increase in annual enteric CH_4 emissions. This scenario could occur in times where there is a growing national inventory of cattle. At this rate of increase both the GWP100 and GWP* give identical values for CO_2-e and CO_2-we, respectively. This would mean that any rate of increase above 1.01% in enteric CH_4 would result in CO_2-we values from the GWP*

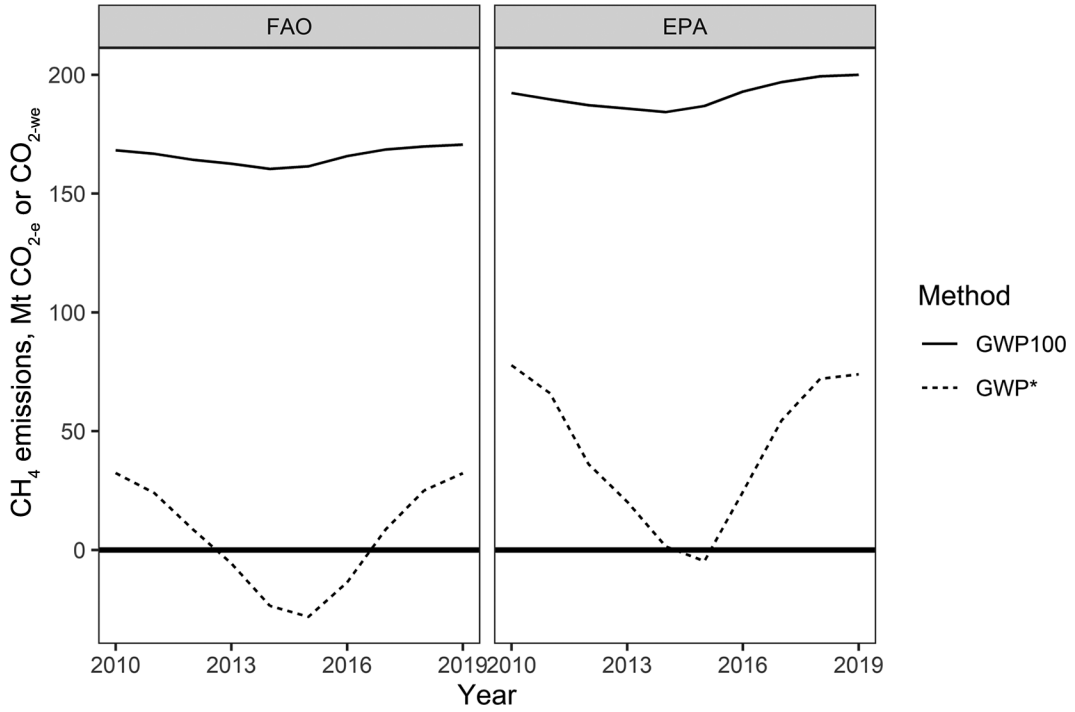


Figure 5. Methane (CH_4) emissions expressed as CO_2 equivalence ($CO_{2\text{-}e}$) or CO_2 warming equivalence ($CO_{2\text{-}we}$) following the GWP100 or GWP* methodology, respectively. GWP100 = 100-yr global warming potential; GWP* = newer global warming potential*; FAO = Food and Agriculture Organization; EPA = US Environmental Protection Agency.

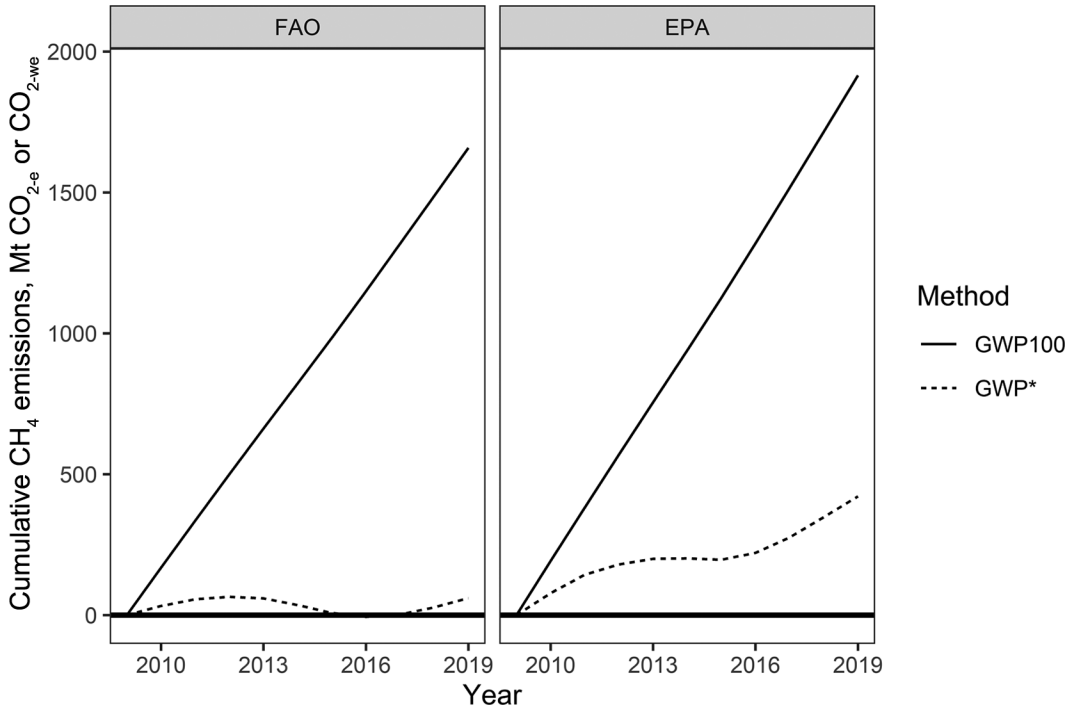


Figure 6. Cumulative CO_2 equivalence ($CO_{2\text{-}e}$) in the case of the GWP100 method and CO_2 warming equivalence ($CO_{2\text{-}we}$) for GWP* from 2010 to 2019 as influenced by the reporting body source, either the Food and Agriculture Organization (FAO) or US Environmental Protection Agency (EPA). GWP100 = 100-yr global warming potential; GWP* = newer global warming potential*.

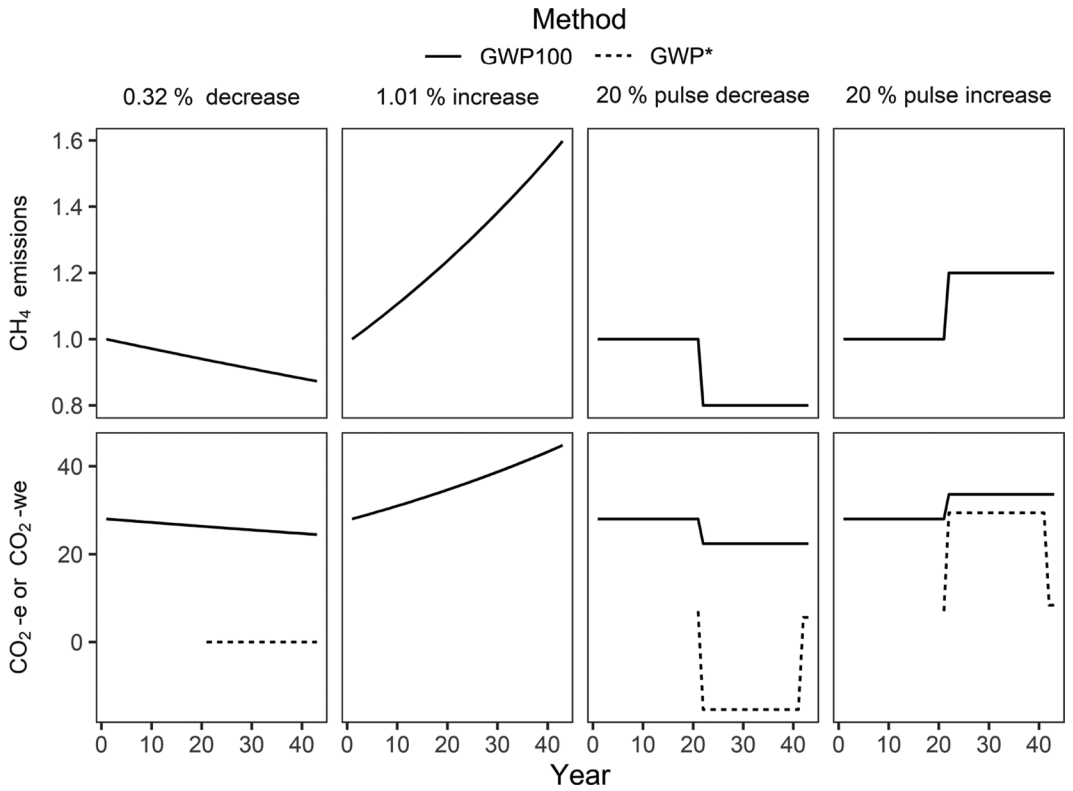


Figure 7. The effect of methodology (GWP100 or GWP*) to relate CH_4 emissions to CO_2 equivalence ($CO_{2\text{-}e}$) for the case of GWP100 or CO_2 warming equivalence ($CO_{2\text{-}we}$) for GWP*. At yr 1 we assume that enteric CH_4 emissions were 1 × what they currently are for US enteric CH_4. The scenarios explored were (1) an annual reduction of enteric CH_4 of 0.32%, (2) a 1.01% annual increase in enteric CH_4 emissions, (3) a 20% pulse reduction in enteric CH_4 at yr 20, or (4) a 20% pulse increase in enteric CH_4 emissions at yr 20. GWP100 = 100-yr global warming potential; GWP* = newer global warming potential*.

method that are greater than the CO_2-e emissions determined using the GWP100 method. Only by keeping enteric CH_4 emissions below an annual growth rate of 1.01% would GWP* make ruminant livestock production appear better in terms of their GHG contributions relative to simply using the traditional GWP100 method. This demonstrates the key point highlighted previously that this new methodology is not a panacea and is in agreement with results demonstrated by Liu et al. (2021). These authors found that for California-specific dairy cattle production, GWP* actually resulted in greater climate impacts relative to GWP100 over the past 35 yr. This is because using GWP* has the potential to calculate a greater CO_2-e for CH_4 compared with GWP100 when animal populations are expanding, as they had in California during much of the modeled time period. This must be considered when discussing issues related to sustainable livestock production as improvements in efficiency alone will not allow us to reach the climate neutral goal outlined by the National Cattlemen's Beef Association (NCBA, 2021); rather, reductions in absolute emissions will be required.

Scenarios 3 and 4 represent a 20% pulse decrease (i.e., sudden adoption of new technology) or increase in enteric CH_4 emissions, respectively. A cause behind a pulse decrease could be rapid adoption of a new enteric CH_4 mitigation technology, such as 3-nitrooxypropanol (Romero-Perez et al., 2015). A pulse increase could be due to a rapid change in management practices, such as areas changing grain processing strategies (i.e., going from steam-flaked corn to dry rolled corn may increase enteric CH_4 emissions by 20%; Hales et al., 2012), for example. In scenario 3 we see, as expected, a 20% decrease in CO_2-e in response to the 20% decrease in CH_4 emissions for the GWP100 method. This is in contrast to a period of time where CO_2-we is negative for 20-yr before increasing back above zero. Thus, adopting a new technology that would have an immediate benefit in CH_4 emission reductions would result in a period where enteric CH_4 would provide a net-negative effect on actual climate warming; however, after 20 yr, this source of emissions would again become a net contributor to warming without further technological developments. Scenario 4 is opposite to scenario 3. A 20% pulse increase in enteric CH_4 emissions causes a concurrent 20% increase in CO_2-e for GWP100 methods, yet results in a larger increase in CO_2-we emissions for the GWP* method. Again, after 20 yr, the industry would reach a new steady state and CO_2-we emissions would again be lower relative to GWP100.

APPLICATIONS

Methane is a potent, yet short lived, GHG, with only a 12-yr lifespan in the atmosphere (US EPA, 2021a). Accordingly, it does not make sense to treat this SLCF like a stock GHG, such as nitrous oxide, which has a 114-yr lifespan in the atmosphere (US EPA, 2021a), and to apply the GWP100 method for both GHG types. Because of this relationship, several climate scientists have suggested the GWP* method to relate CH_4 emissions to a CO_2-we basis, which more closely represent CH_4 actual contribution to climate warming. Despite there being large differences in the US enteric CH_4 emission estimates between the FAO and EPA reporting bodies, which is largely driven by the accounting tier that was used (tier 1 and 2, respectively), using the GWP* method instead of GWP100 greatly reduces the implied contribution of enteric CH_4 emissions to climate warming for both data sets. It is important to note that in periods where emissions are increasing (greater than a 1.01% annual increase), GWP* would actually result in an implied greater contribution to climate warming than the GWP100 method. As such, the adoption of GWP* is by no means a panacea in fixing GHG emissions from livestock production. However, if or when GWP* is adopted by reporting bodies to relate CH_4 emissions to a CO_2-e, there should be a paradigm shift in how society views the decrease of enteric CH_4 emissions. Rather than being viewed as a significant contributor to the changing climate, GWP* indicates that a small decrease in enteric CH_4 emissions can lead to a net decrease in climate warming. Yet, after a period of time, any decrease in enteric CH_4 would eventually create a new steady state and enteric CH_4 emissions would again start contributing to warming. Thus, reducing CH_4 emissions could be viewed as a short-term solution to reduce total anthropogenic contributions to warming, as our society transitions to lower-emission technologies.

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