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Comparison of Methodologies Used to Estimate Enteric Methane Emissions and Warming Impact from 1920 to 2020 for U.S. Beef Production

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Abstract: Estimates of historical enteric methane emissions by US beef cattle using various methodologies recommended by IPCC were compared, then translated using two expressions of carbon dioxide equivalence. Three existing methodologies (Tier 1, Tier 2, and Tier 3 as used by FAO, EPA, and NASEM, respectively) were compared using a common time series (1920 to 2020) for each sector of the US beef cattle production system. Annual enteric methane emissions were converted to annual CO_2 equivalents for global warming potential on a 100-year horizon (GWP_{100}) and CO_2 warming equivalents (GWP*) to compare two expressions of methane equivalence to carbon dioxide. While the ranking of estimates among methods was stable, the magnitude of difference between the methods increased over time. In 1920, the Tier 3 method estimated emissions 16% greater than Tier 1; this difference increased to 60% greater in 2020. Cumulative GWP* ranged from 8.9% below to 29.4% below cumulative GWP_{100} in 2020, depending upon method; differences in annual emissions metrics were larger, with GWP* metrics ranging from 261% below to 123% above GWP_{100} expression. While several methods exist to generate emissions inventories, method choice results in substantial differences in direct emissions estimates and carbon dioxide equivalence.

Keywords: beef cattle; enteric methane; global warming potential; sustainability

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1. Introduction

Cattle have been assigned a relatively large carbon (C) footprint (10 to 32.4 kg carbon dioxide equivalents (CO_2e)/kg liveweight) [1] in comparison to other livestock species [2]. As a result, it has been assumed that beef production has a negative environmental effect [3,4]. Estimates of enteric methane production, resulting from fermentation of forage and other human-inedible feedstuffs, are typically expressed equivalent to CO_2 and comprise a large portion of beef production's C footprint [5,6]. These estimates result from the emissions inventory methodology selected and the choice of 'equivalence' measures used to express different greenhouse gases using standard units, most commonly, some carbon dioxide equivalent.

Three tiers of livestock methane emissions inventory estimation were established by the Intergovernmental Panel on Climate Change (IPCC) [7] as an element of the guidelines for greenhouse gas (GHG) inventory reporting at the country level. Tiers were developed to accommodate varying levels of data availability [7]. The three tiers yield different estimates for a given population [8–11]. Xue et al. [10] estimated methane emissions using IPCC [7] Tier 1 and 2 methodologies and found a Tier 2 approach led to lower estimated emissions inventory compared to the Tier 1 approach. Conversely, Ominski et al. [8] reported lower estimates using Tier 1 methods compared to Tier 2. These authors also observed that empirical outcomes ranged from 12.6% below to 32.6% above Tier 2 values. Among cattle of the same class, variation in enteric methane emissions exist [12]. Diet quality, intake, and feed additives lead to variation in emissions factors (kg CH_4 per animal) [13–15] resulting in absolute emissions uncertainty and modeling error. The IPCC periodically reviews and updates recommended methodology, which may further confuse estimation of apparent emission inventories over time. The most recent refinement of methods [16] has yet to be implemented by policy makers and reporting agencies.

Cattle are implicated as a major source of increased methane emissions due to reported increases in population size [2,17,18]. However, the structure of the U.S. beef industry has changed over the last 100 years; notably, the proportion of the population represented by each animal class has changed. In some regions, cow body weight has increased; and in some systems, cattle are finished in a shorter amount of time. As a result of these industry changes, changes in methane emissions may not be directly (linearly) aligned with changes in total cattle population.

The challenges in emissions characterization due to inventory methodology are compounded using conversion metrics to a carbon dioxide 'equivalent' value. Emissions statements expressed as total mass or using IPCC [19] sanctioned expressions of equivalency may yield substantially different outcomes. Recently, CO_2 warming equivalents (GWP*) has been proposed as a more accurate metric to account for the climate warming effects of methane compared to global warming potential on a 100-year horizon (GWP_{100}) [20,21] and is recognized by the IPCC as an appropriate metric. Because GWP* depends upon changes in emissions over time, the issues of emissions inventory estimation and accounting for structural changes in the beef industry become increasingly important.

Our objective was to compare estimates of historical enteric methane emissions by US beef cattle using various methodologies recommended by IPCC [7] applied to a common cattle population time series. Additionally, we aimed to translate enteric methane emissions using two expressions of carbon dioxide equivalence, and their interaction with emissions estimate method. Finally, we evaluated the effects of these estimates on apparent methane intensity of US beef production over time.

2. Materials and Methods

Methods for estimation of enteric methane emissions used in greenhouse gas inventory reporting have been outlined by the IPCC [7]. The Food and Agriculture Organization of the United Nations (FAO) uses a Tier 1 approach to estimate country and global enteric methane emissions. This Tier 1 method is the simplest of the three tiers and requires the least amount of data, as a fixed amount of methane is assumed for each animal.

The United States Environmental Protection Agency (EPA) uses a Tier 2 approach to estimate enteric methane emissions of beef cattle in the United States as a component of the US greenhouse gas inventory reporting program [22]. This method requires more detailed information about animal classes, body weights, nutrient requirements, and dietary information.

Similarly, National Academies of Science, Engineering and Medicine (NASEM) [23] has published enteric methane prediction equations that can be used and scaled to a national level using existing data. Using NASEM methodology can be considered a Tier 3 approach as these equations incorporate further dietary detail compared to the EPA's Tier 2 methods. For this analysis, we chose to compare three existing methodologies (Tier 1, Tier 2, and Tier 3 as used by FAO, EPA, and NASEM, respectively) using a common population time series (1920 to 2020) for each sector (cow-calf, stocker, and feedlot) of the US beef cattle production system.

Animal classes for beef systems include bulls, cows, calves nursing cows, heifers held for replacement, stocker cattle (grazing animals intended for slaughter, which may be placed into a feedlot prior to slaughter), and animals in a feedlot. Animal class level data required to estimate methane inventory using the three methodologies were animal inventory, animal weights, growth performance assumptions, and nutrient profile of diets. Historical animal inventories were obtained from National Agricultural Statistics Service (NASS) [24]. Prior to the issuance of the cattle on feed report (1920–1941), number of cattle on feed were estimated using the 8-year average (1942–1950) of the proportion of feedlot cattle represented in the total inventory. This 8-year average was chosen because it was the closest to the missing date range of cattle on feed inventory and cattle on feed was relatively constant during this 8-year period. An average value was chosen over a linear regression estimate because it was assumed there was little growth cattle on feed prior to 1942. Growth in cattle on feed inventories occurred rapidly after 1950 due to structural changes in the beef industry. Inventory data by year are provided in Supplementary Material (Table S1).

The US beef production system is often described by sectors. The cow-calf sector includes the animal classes: bull, cow, calves nursing cows, and heifers held for replacement. Calves nursing cows were excluded from this analysis because NASS [24] does not differentiate between beef and dairy calves in their inventory estimates and the IPCC [7] assigns an emissions factor of 0 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$ to nursing calves. The stocker sector includes stocker cattle (as defined above), and the feedlot or finishing sector includes the feedlot class. Because NASS [24] reports do not designate cattle specifically to the stocker sector but does report steers and heifers greater than 227 kg body weight (BW), the number of stocker cattle was estimated as the difference between total steers and heifers greater than 227 kg and number of cattle on feed.

Historical animal weights of various classes were obtained from NASS [24] and United States Department of Agriculture, Economic Research Service (USDA-ERS) [25,26]. Bull carcass weights were obtained from NASS [24] and converted to body weight by dividing by 0.50 with the assumption dressing percentage was constant across time for bulls. Historical weaning weight of calves were estimated using the average response from linear regressions published by Lalman [27] and Nadarajah et al. [28] which predict weaning weight from cow body weight. Cow body weights were adjusted from cow carcass weights obtained from NASS [24] with the following assumptions: cow dressing percentage was constant across time at 52% and cows slaughtered were at a body condition score of 4 on a 1 to 9 scale. Stocker cattle weights were estimated as the average of weaning weight and feeder cattle weights. Feeder cattle weights were estimated from placement data from NASS [24] and USDA-ERS [25,26,29,30]. Feedlot cattle weights were an average of feeder cattle weights and slaughter weights reported by NASS [24]. Historical weights used in this analysis are presented in the supplementary information (Table S2).

Nutrient profiles of grazing diets were assembled from descriptions of forages commonly utilized and are assumed constant across time. Nutrient profiles of grazed forages in cow-calf and stocker operations have not considerably changed across the timespan evaluated, therefore these nutrient profiles were held constant across time and were obtained from NASEM [23]. Feedlot diets periodically changed because of technological advancement and dietary ingredient availability [31–36]. Historical nutrient profiles of diets are also available in the supplementary information (Tables S3–S5).

Animal class inventories were multiplied by an emissions factor (53 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$) [7] according to the FAO methodology (Tier 1) to estimate annual animal class emissions.

An emissions factor (kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$) for each animal class was determined according to the Tier 2 approach of EPA [22]. Required gross energy intake (GEI, MJ/d) for each class was calculated according to Equation 10.21 in IPCC [7]. Briefly, GEI was estimated as the sum of GE required for maintenance, activity, lactation, work, pregnancy, and growth. Required GEI was multiplied by enteric methane yield (Y_m, MJ CH_4/MJ GE) and converted to kg of methane (55.65 MJ/kg CH_4). Y_m values were 6.5% (grazing cattle) or 3.9% (feedlot cattle) as recommended by IPCC [7] and Kebreab et al. [37], respectively. Daily enteric methane emissions were multiplied by 365 d to compute an enteric methane emissions factor. Emissions factor for a class was multiplied by class level inventory within year to determine class level annual enteric methane emissions. The sum of annual class level emissions within a year represents total annual emissions inventory.

To represent a Tier 3 estimate, equations published by NASEM [23] were utilized. In addition to nutrient profiles of diets, use of the NASEM [23] set of enteric methane equations required estimates of dry matter intake, unlike the Tier 2 approach, which is based on estimates of energetic requirements. Dry matter intake (kg/d) was predicted for each animal class using Equations 19–88, 19–89, 19–92, and 19–94 from NASEM [23]. Equations 16–8, 19–127, 19–128, and 19–129 were used to estimate enteric methane from grazing animals (cattle in the cow-calf and stocker sectors) and Equations 16–9, 19–135, 19–136, and 19–137 were used to estimate enteric methane production from animals consuming high concentrate diets (cattle in the feedlot sector) as recommended [23]. Enteric emissions for each animal class were summed within its respective sector of the beef value chain then each sector was summed within year to determine annual total enteric methane production.

Equations 16–8 and 16–9 in NASEM [23] represent a synthesis of other empirically derived equations for enteric methane emissions (those outlined in Chapter 19). The Beef Cattle Nutrient Requirements Model (BCNRM; see [23]) utilizes these published equations to generate estimates of uncertainty/variability in enteric methane production. The minimum, maximum, and mean values from all NASEM [23] estimates were recorded by class and totaled as previously described. These values are used to display a range of uncertainty in enteric methane emissions as intended by NASEM [23].

Compiled annual enteric methane emissions from 1920 to 2021 were converted to annual CO_2 equivalents for global warming potential on a 100-year horizon (CO_2e, GWP_{100}) and CO_2 warming equivalents (CO_2-we, GWP*) to compare two expressions of methane equivalence to carbon dioxide. Estimation of annual GWP_{100}-CO_2e was performed as annual enteric methane emissions (kg CH_4) multiplied by 28 kg GWP_{100}-CO_2e/kg CH_4 (AR5 recommendation for GWP_{100} without climate-carbon feedback) [38].

Annual GWP* CO_2-we was calculated according to Lynch et al. [20] as:

$$CO_2\text{-we} = GWP_{100} \cdot ((4 \cdot \text{EmissionsCH}_4{}^{t}) - (3.75 \cdot \text{EmissionsCH}_4{}^{t\text{-}20})), \quad (1)$$

where $\text{EmissionCH}_4{}^{t}$ was the target year enteric methane emissions rate (kg/yr) and $\text{EmissionsCH}_4{}^{t-20}$ was the enteric methane emissions rate (kg/yr) from 20 years prior to the target year. For years 1920 to 1939, emissions for all years $t - 20$ were assumed to be constant at 1920 estimated emissions values generated by the respective method of estimation.

Enteric methane emissions per kg of beef produced in the United States were calculated to determine enteric methane intensity of beef production. Beef production from 1921 to 1929 was obtained from Economic Research Services [25] and beef production from 1930 to 2020 was obtained from NASS database [24]. Historical beef production data are available in the Supplementary Information.

3. Results and Discussion

3.1. Enteric Methane Emissions across Time

Estimated enteric methane emissions across time were greatest when the Tier 3 was applied, while the Tier 1 method generated the lowest emissions estimates and the Tier 2 methodology estimated intermediate values (Figure 1). While the ranking of estimates among methods was stable, the magnitude of difference increased over time. In 1920, the Tier 3 method estimated emissions 16% greater than Tier 1 emissions estimate, over time the difference increased such that the Tier 3 estimate was 60% greater than Tier 1 emissions estimate in 2021. Similarly, Tier 1 and 2 methodologies also diverge over time. In 1920, the Tier 1 and 2 methodologies estimated similar enteric methane emissions (within 3%); for 2021, the Tier 2 method yielded an estimate 20% greater than Tier 1.

Cattle inventory directly affects total emissions estimates in all methods applied. In the Tier 2 and 3 methodologies, body weight affects the emissions factor, while the Tier 1 methodology uses a constant emission factor. Individual mean weight of cattle has increased since the 1970's while inventory has declined over the same period (see Supplementary Material). As a result, the Tier 1 estimates a decline in annual enteric methane emissions. However, because body weight is included in the Tier 2 and 3 methodologies, emissions factors (per animal) increase, but are largely offset by decreases in inventory such that annual emissions are stable (Tier 2) to slightly increasing (Tier 3) over time. The difference in the Tier 2 and 3 methods results from differences in GEI estimates, which are nutrient requirement based in the Tier 2 method but based on estimated dietary intake in the Tier 3 method. Dietary intake is a function of body weight and diet nutrient profile, and the divergence between the Tier 2 and 3 methods is thus likely driven by the difference in estimating GEI.

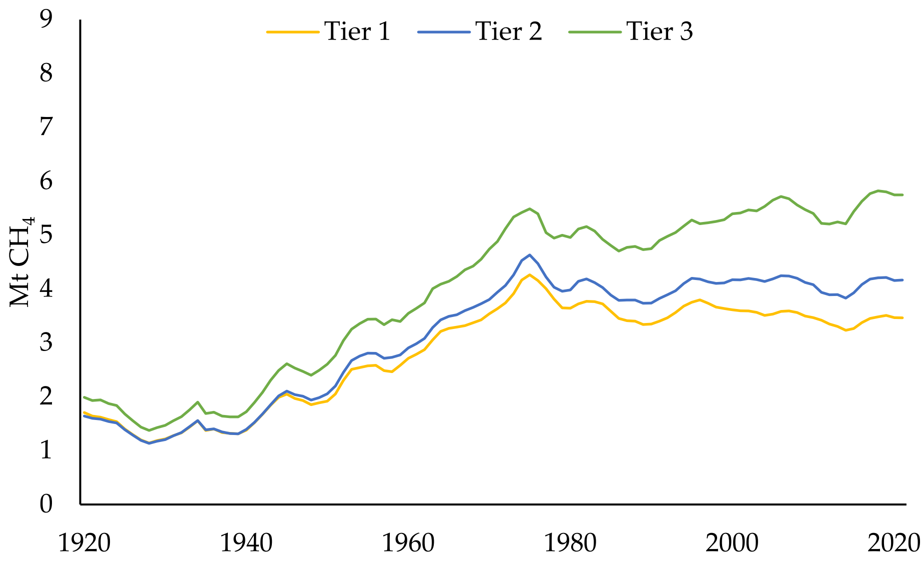


Figure 1. Total enteric methane emissions from 1920 to 2020 using Tier 1, 2, or 3 methodologies.

While the Tier 1 emissions factor used in this analysis is constant (53 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$), the IPCC recently updated (increased) the specified Tier 1 emissions factor for North American beef cattle to 65 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$ [16]. Application of this emissions factor would result in a 22.6% increase in estimated annual emissions from the displayed Tier 1 estimates, creating greater alignment between Tier 1 and 2 emissions estimates.

Wolf et al. [39] estimated that global enteric methane emissions in 2011 were 8.4% greater than values suggested the IPCC [7] Tier 1 methodology when updates to animal body mass, diet quality, and diet quantity were made by global region. Within the US, regional variation in emissions also likely exists; Hristov et al. [11] reported emissions may vary by −15.6 to 16.9% of mean enteric livestock emissions for the continental US depending on location. Similarly, NASEM [23] recognizes that large variation in prediction of enteric fermentation exists between models. As an indicator of the potential range in enteric methane production, output from Beef Cattle Nutrient Requirements Model in NASEM [23] reports the minimum, mean, and maximum estimates of enteric methane production based on a series of equations from the primary literature. When using primary equations published by NASEM [23] for estimating enteric methane, year 2020 emissions estimates range from 3.05 to 7.17 Mt, representing a ±40% variation from mean enteric methane emissions (Figure 2). The range of estimates observed using the Tier 3 primary equations encompasses the estimates from Tier 1 and 2, and the Tier 3 synthesis equation estimates displayed in Figure 1.

In the present study, the Tier 3 synthesis equations developed by NASEM [23] result in enteric methane production estimates that increase from 1975 to 2020, despite the substantial reductions in animal inventory over that time period. All of the series (minimum, mean, and maximum) generated from the Tier 3 source equations generate lower estimates of enteric methane production in 2021 than 1975; the trendlines for each series are neutral (estimates of maximum productions) to down trending (mean and minimum estimates). Greater estimates of total enteric methane emissions over time from the synthesis equation are driven by higher estimated methane production in the cow-calf sector compared to the mean of the primary equations. Tier 3 synthesis equations for stocker and feedlot cattle resulted in lower emissions estimates than the mean of the primary equations (feedlot, 34.5 vs. 43.9 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$; stocker, 58.3 vs. 63.7 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$), but resulted in a greater emissions factor for cows (117.3 vs. 96.5 kg $CH_4 \cdot animal^{-1} \cdot yr^{-1}$). As a result, both the total emissions estimates and the allocation of emissions among sectors is dependent upon the inventory method selected (Figure 3).

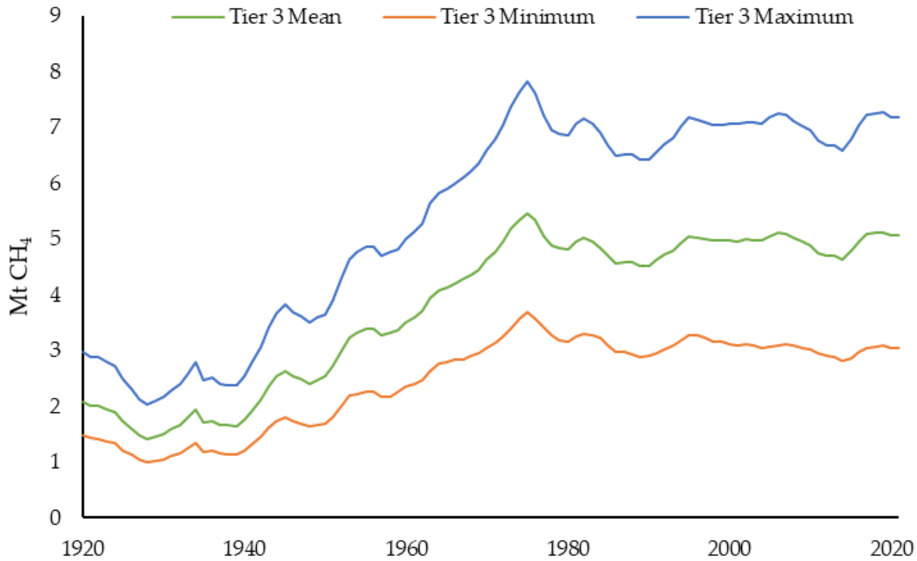


Figure 2. Mean, minimum, and maximum of CH_4 emissions (Mt) using Tier 3 methods from 1920 to 2020.

Herd expansion in the United States occurred from 1920s to the mid-1970s and is reflected in total annual enteric methane emissions in Figure 3. A peak in enteric methane emissions occurred in the mid-1970s which corresponds to peak beef cattle inventory. Additionally, the historic cattle cycle of expansion and contraction over a 10-year period is apparent when annual enteric methane emissions are plotted across time. Since the mid-1970s, cattle size has increased, both in mature cow size and finished weights (see supplementary material). The increase in cow body weight and finished animal weights result in Tier 1 estimates of emissions that decline over time with inventory (Figure 3a); Tier 2 estimates of emissions depart from population trends as Tier 2 methods rely on body weight. The Tier 2 method relies on estimates of energy requirements, which scale with metabolic body weight ($BW^{0.75}$); therefore, emissions estimates do not increase as rapidly as body weight. The rate of increase is offset by population decline, such that emissions estimates have a neutral trend (Figure 3b). Tier 3 methods rely on estimates of diet intake, rather than requirements, and utilize different equations to estimate emissions. Specifically, the equation used to estimate intake is linearly related with BW, and the result indicates BW increased faster than the declining trend in population. This effect, in addition to the differences in per animal emissions factors resulting from the different equations, result in emissions estimates that increase over time (Figure 3b).

3.2. Contribution by Sector to Total Enteric Methane Emissions

Throughout the period analyzed, the cow-calf sector makes the greatest contribution to beef production's enteric methane emissions regardless of the method of estimation (Figure 4), with the proportion of total emissions allocated to each sector varying both over time and among estimation methods. The dominance of the cow-calf sector relative to stocker and feedlot sectors is consistent with other reports [6], and results from relatively larger population size (Tier 1 or Tier 2 methods), reliance on lower quality diets (Tier 2 methods) and greater body weights. Importantly, the reliance on these diets also reduces the reliance on other commodities and increases the yield of high-quality protein for human consumption relative to human consumable protein inputs [40]. The tradeoff to reducing methane emissions from this sector is an increase in intensification and utilization of feedstuffs that may also be directly used for human consumption.

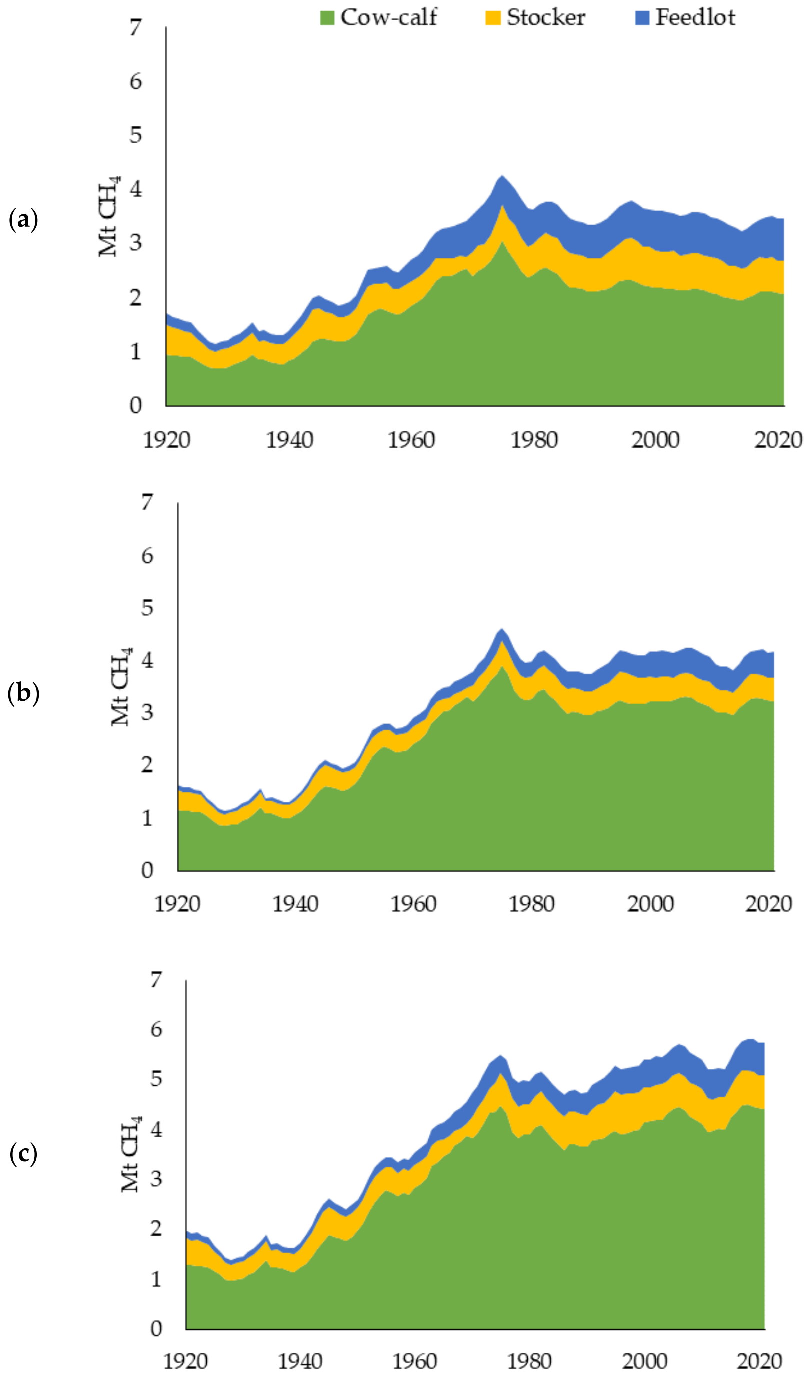


Figure 3. Enteric methane emissions by animal class from US beef cattle, 1920 to 2020, using (**a**) Tier 1 methodology; (**b**) Tier 2 methodology; (**c**) Tier 3 primary equation.

In the 1920s, the stocker sector accounted for 25% of total enteric methane emissions. However, over time the stocker sector's contribution to total enteric methane emissions has declined to 12% (Figure 4). Historically, cattle spent a greater amount of time in the stocker sector (i.e., steers and heifers greater than 226.8 kg) since cattle were often 2 to 3 years old when taken to the feedlot or slaughtered in the early 1900s. This extended time to harvest resulted in a greater proportion of the annual beef cattle inventory in the sector, with greater enteric methane production attributed to grazing cattle when using Tier 2 inventory methods.

(a)

(b)

(c)

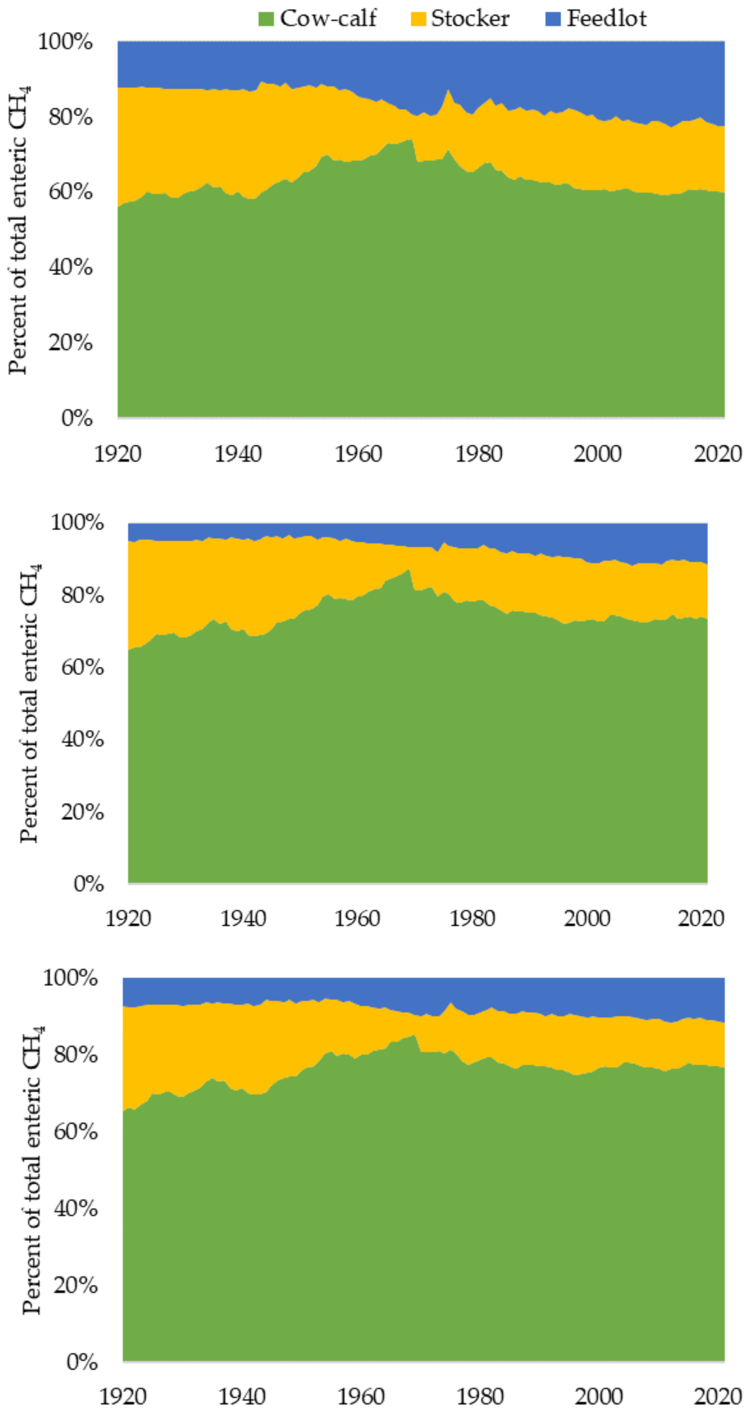


Figure 4. Contribution to enteric methane emissions by sector of beef value chain from 1920 to 2020, using (**a**) Tier 1 methodology; (**b**) Tier 2 methodology; (**c**) Tier 3 primary equation.

Substantial growth in capacity to place cattle on feed in the 1950s and 1960s resulted in growth of feedlot sector and accelerated time to slaughter. Cattle on feed increased 193% from 1920 to 1960 (3.9 million to 7.5 million head), resulting in increased enteric methane emissions from the sector during the same period corresponding to the reduced emissions from the stocker sector. Currently, the feedlot sector accounts for 11% of total enteric methane emissions compared to 7% in 1920 when using the Tier 3 method (Figure 4c).

When comparing the relative contribution of the production sectors the Tier 1 methodology overweights feedlot contributions and underweights cow-calf sector contributions by applying the constant emission factor (53 kg CH_4·animal^{-1}·yr^{-1}) across all animal classes.

This effect can be more pronounced when making regional comparisons as production system may vary substantially among regions. Those with well-developed feedlot sectors appear to be greater emitters than may be the case, while those reliant on grazing systems may have emissions inventories that are skewed downward. When using the Tier 2 or 3 approaches, the proportion of emissions from individual production sectors may better reflect actual emissions because these methodologies estimate an emissions factor for each animal class based on weight, diet, and requirements.

3.3. Enteric Methane Intensities across Time

Apparent enteric methane intensity of beef production (kg CH_4/kg beef) has decreased since 1920 regardless of emissions inventory methodology (43% reduction on average; Figure 5), consistent with other reports [41,42]. Cattle population declined from 1920 to 1928 due to major drought, resulting in reductions in annual enteric methane emissions estimates (Figure 1). This liquidation of cattle population resulted in steady to slight increases in beef production from 1920 to 1927. The reduction in enteric methane intensity in the 1920s was a product of reduced enteric methane emissions from a smaller cattle population and greater production of beef resulting from herd liquidation. Capper [42] estimated an 18.7% reduction in methane emissions intensity for the 30-year period from 1977 to 2007, comparable to the 20% reduction in methane emissions intensity during the 1977–2007 timespan using the Tier 1 methodology. However, estimates for this 30-y span using other methodologies differ in magnitude (9% reduction, Tier 2) or direction (5.6% increase, Tier 3) of change in enteric methane emissions intensity.

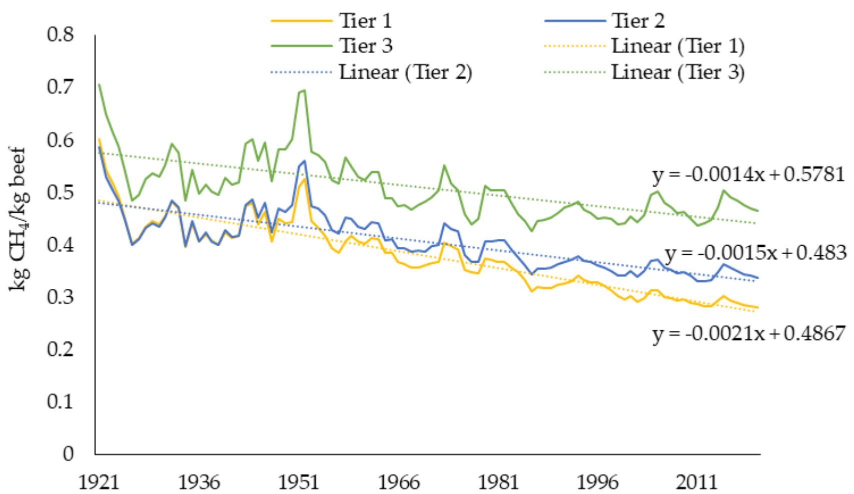


Figure 5. Enteric methane intensity (kg/kg beef produced) from 1921 to 2020 using Tier 1, 2, and 3 methods. Standard errors of the slope parameter for Tier 1 = 0.000102; for Tier 2 = 0.000113; and for Tier 3 = 0.00015.

If the change over time is estimated as the difference in the means of 5-year periods (1975–1979 versus 2016–2020) rather than as single year differences, the Tier 3 method would indicate that enteric methane intensity has remained constant over the last 42 years. Cow body weight is a variable used in the Tier 3 method for estimating enteric methane emissions, and cow body weight has increased approximately 140 kg since the 1970s. This increase in cow body weight directly affects estimates of enteric methane emissions using Tier 2 and 3 approach, and those increases offset improvements in productivity (kg beef produced per unit of inventory).

The Tier 1 method does not require animal size as an input, so emission intensities vary inversely with productivity where greater production per animal in inventory reduces emissions intensity. The Tier 2 method is based on animal requirement estimates, which scale with $BW^{0.75}$. Because beef production is expected to change directly (linearly) with animal size, as body weight increases output increases at a faster rate than animal requirements, therefore emission intensities decrease but not as rapidly as with the Tier 1 method. In the primary NASEM equation for Tier 3, body weight is included as a linear predictor, and thus increases in body weight and productivity may scale at similar rates, such that no net impact on intensity is realized. It is important to recognize that these model predictions differ due to construction; there is limited ability to determine the accuracy of any one approach.

3.4. Estimated Annual CO_2 Equivalent Emissions

A number of methods have been developed that attempt to scale the relative impact of short-lived climate pollutants (SLCP; e.g., methane) to carbon dioxide [21,38,43]. The Global Warming Potential estimated on a 100-year time horizon (GWP_{100}) metric has been widely applied, due in part to its relatively simple calculation (mass emissions are scaled by a constant). Therefore, GWP_{100} is scaled directly to annual emissions, which in turn varies according to the inventory method used. Using GWP_{100}, annual enteric methane emissions (kg CO_2e) were lower in the early 1900s because the cattle population was smaller relative to following decades (Figure 6a). As cattle population expanded to meet growing beef demand in the mid-1900s, estimated enteric methane emissions increased regardless of the method used, and differences among methods reflect the differences in estimated output as described above.

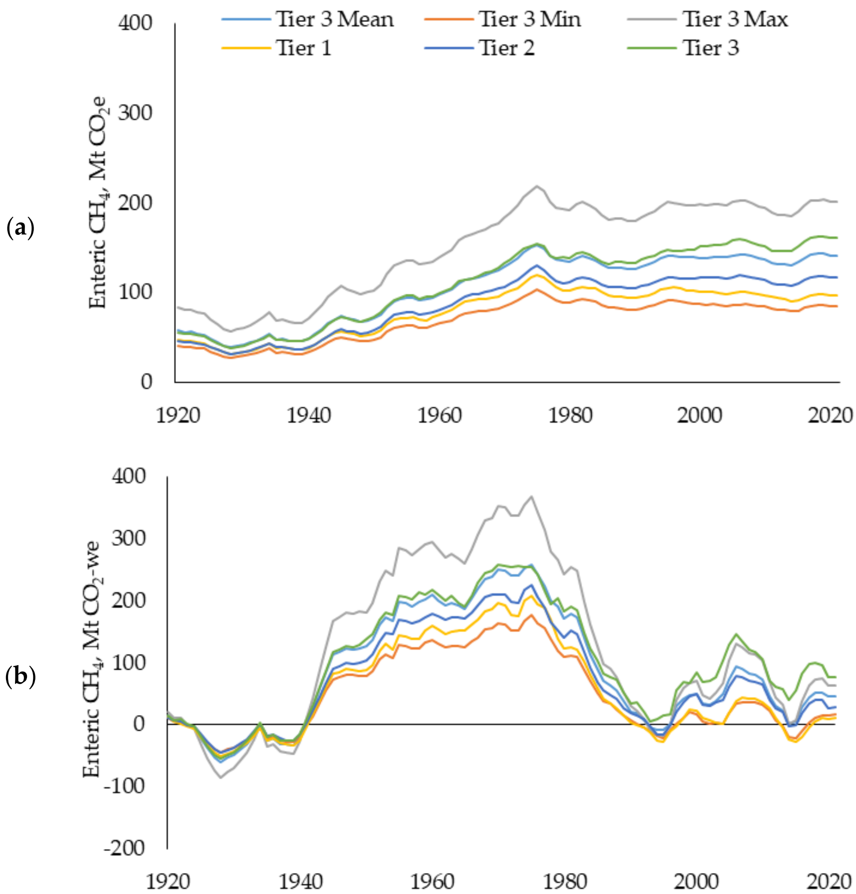


Figure 6. Annual CO_2 equivalent emissions from enteric methane between 1920 and 2021 by US beef cattle. (**a**) Estimated using GWP_{100}; (**b**) Estimated using GWP*.

The GWP_{100} metric incorporates the lifetime of methane as a component of radiative forcing dissipation of a single pulse emission over time [38], but cannot recognize that constant emissions of a short-lived gas result in subsequent equilibrium in atmospheric concentration, making interpretation at any time but the specific time horizon following a pulse emission difficult. The GWP* metric [21,44] attempts to account for the lasting perturbation of a pulse emission along with the effects of differential rates of emission over time on atmospheric stock accumulation (i.e., flow differential) and this metric tracks warming responses over time resulting from methane emissions more accurately than the GWP_{100} metric [20,44]. As a result, changes in emissions rates are a primary driver in the GWP* metric, rather than single year emissions. Estimated GWP* warming equivalent emissions are greater during herd expansion era (Figure 6b) compared to GWP_{100} estimated equivalents (i.e., when the current year mass emissions are greater than the emissions from 20 years prior). As the cattle population declined after the mid-1970s, and weights of cattle increased after the 1970s, annual warming equivalent emissions using GWP* dropped to near zero and have remained lower in comparison to equivalents based on GWP_{100}; annual GWP_{100} equivalent emissions appear relatively constant since the 1970s. While the comparison between GWP* and GWP100 creates the appearance of greater volatility for the GWP* metric, the choice and interpretation of these metrics should be driven by its intended application [19].

3.5. Estimated Cumulative CO_2 Equivalent Emissions

Cumulative CO_2e emissions are a sum of annual emissions equivalents over time. The estimated warming impact of methane is related to the 100-year cumulative CO_2e emissions based on GWP_{100}. By design, cumulative CO_2e emissions will either increase (positive annual emissions) or stay constant (zero annual emissions). A reduction in cumulative CO_2e emissions would indicates a methane sink (negative annual emissions) which can occur when atmospheric degradation exceeds annual emissions, resulting in a reduction in atmospheric burden of methane. A wide range of emissions were estimated using the various methodologies presented, leading to greater uncertainty of actual effect on climate from beef cattle's enteric methane (Figure 7). However, emissions over time increase at a greater rate during herd expansion then plateau once herd expansion ceases.

(a)

(b)

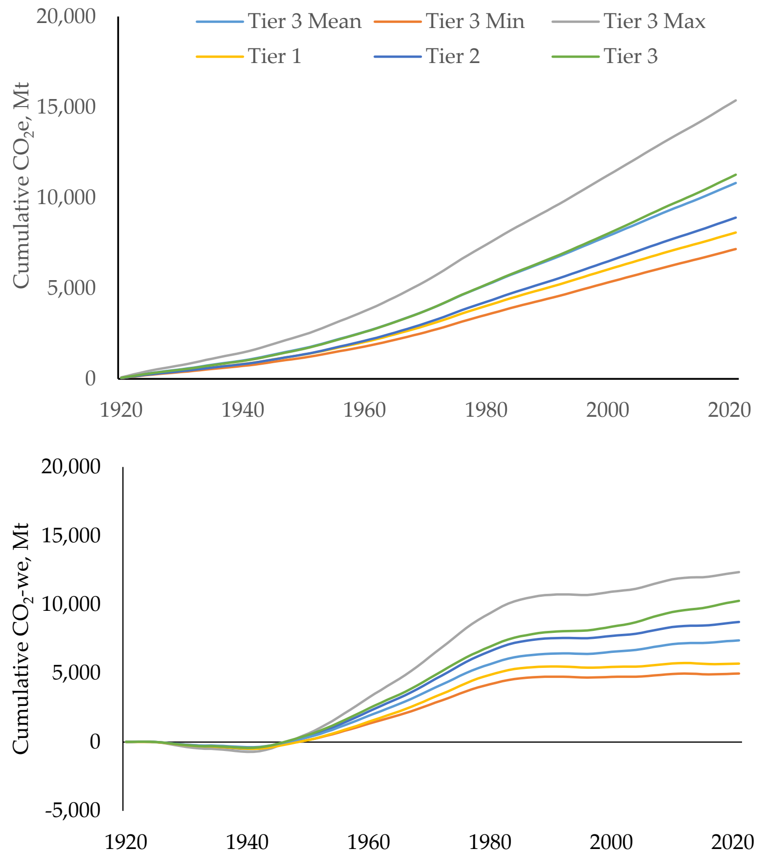
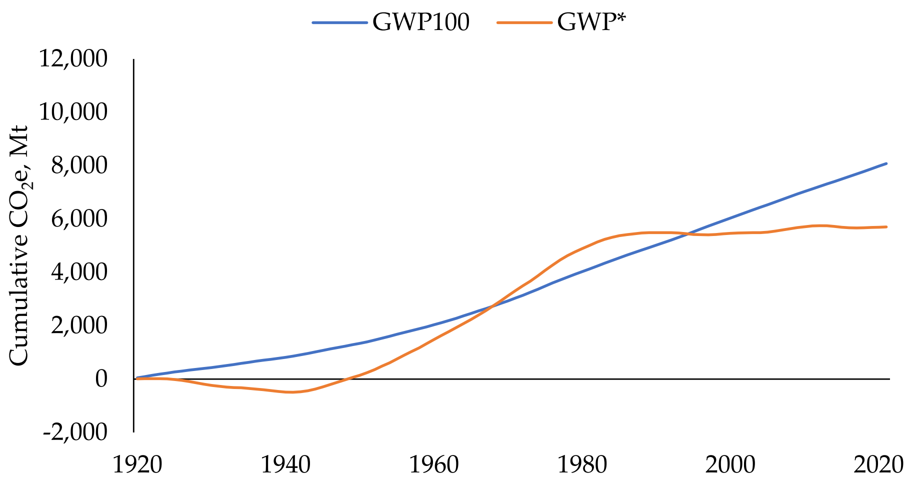


Figure 7. Cumulative CO_2 equivalent emissions from enteric methane between 1920 and 2021 by US beef cattle. (**a**) Estimated using GWP_{100}; (**b**) Estimated using GWP*.

GWP_{100} was developed to estimate the effects of pulse methane emissions on warming potential over a 100-year period. Because this analysis used a 100-year period, cumulative estimates of warming impacts using GWP_{100} or GWP* (Figure 8) would be expected to converge for any mass emissions method chosen. In the current analysis, cumulative GWP* in 2020 (year 101) ranges from 8.9% below to 29.4% below cumulative GWP_{100}, depending upon method. Trends across time for GWP_{100} and GWP* were similar amongst methods. The difference among annual emissions metrics is substantially larger, with GWP* metrics ranging from 261% below to 123% above the GWP_{100} expression for a given year, dependent upon mass emissions estimation method. From 2001 to 2020, annual GWP* warming equivalent emissions are always lower than GWP_{100} equivalents, with the size of difference depending on method chosen to estimate mass emissions. The Tier 1 method results in the greatest difference between GWP* and GWP_{100}, with GWP* varying among years by at least 56% below and as much as 131% below the GWP_{100} equivalent. Using the Tier 3 method (Equations 16–8 and 16–9) results in the smallest differences among equivalence expressions, where GWP* ranges from at least 8.6% below to as much as 72% below GWP_{100} estimates, and the Tier 2 method is intermediate, with GWP* warming equivalents at least 34.7% below to as much as 101% below GWP_{100} equivalents.

(**a**)



(**b**)

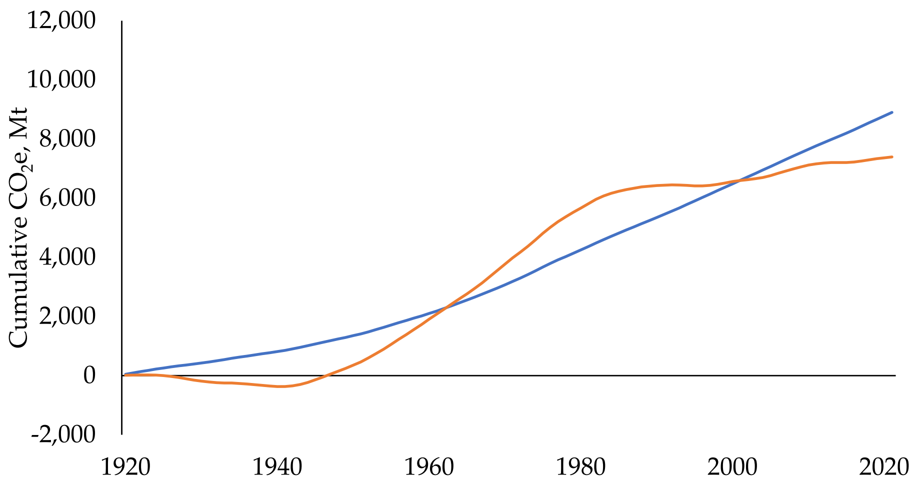


Figure 8. *Cont.*

(c)

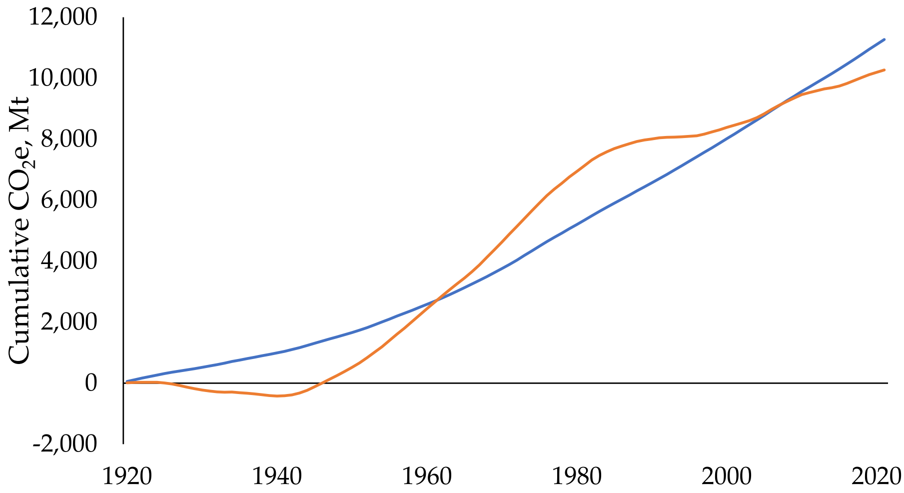


Figure 8. Comparison of cumulative CO_2e emissions using GWP_{100} and GWP* based on (**a**) Tier 1 methodology; (**b**) Tier 2 methodology; (**c**) Tier 3 primary equation.

3.6. Conclusions

Methane emissions by beef cattle have received significant scrutiny. Several 'standard' methods of evaluation can be applied to generate emissions inventories; however, the choice of method results in substantial differences in emissions estimates. This variability among methods would be compounded if variance associated with the underlying assumptions were also included (i.e., animal inventory or body weight estimates). The Tier 2 method described by IPCC [7] explicitly includes an uncertainty of ±33% in methane yield (Y_m, the conversion of gross energy intake to enteric methane), although this uncertainty is rarely included in stated inventory values. This estimate of uncertainty in Y_m should translate to the emissions factor used for Tier 1 estimates, but the value is typically taken as a fixed constant. Additional compounding error is inherent in estimates of animal requirements, diet nutrient values, and dietary conversion to gross energy intake on which the Tier 2 methods are based.

Ultimately, attribution of climate impacts that drive behavioral or policy recommendations must be based on estimates with some indication of confidence. At the least, variance among methodologies might be used as a minimal indicator of confidence, as in NASEM [23]. The resulting range in emissions estimates should be translated to expressions of carbon dioxide equivalence if such metrics are applied for a particular purpose. Use of a single method, without indication of uncertainty, can lead to inappropriate attribution to a particular sector of production within a region, or among regions. Use of different methods across regions or among different reports exacerbates this issue. All of these challenges can lead to inappropriate prioritization in proposed mitigation schemes, perhaps with significant consequences to land use and food production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142417017/s1. Table S1: Annual inventory of beef cattle classes from 1920 to 2021. Table S2: Estimated body weight by animal class from 1920 to 2021. Table S3: Assumptions for diet characteristics of the cow-calf sector from 1920 to 2021. Table S4: Assumptions for diet characteristics of the stocker sector from 1920 to 2021. Table S5: Assumptions for diet characteristics of the feedlot sector from 1920 to 2021. Table S6: Annual beef production from 1920 to 2021.

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