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Methane emissions from California dairies estimated using novel climate metric Global Warming Potential Star show improved agreement with modeled warming dynamics

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Introduction: Carbon dioxide (CO_2) and methane (CH_4) are two of the primary greenhouse gases (GHG) responsible for global warming. The "stock gas" CO_2 accumulates in the atmosphere even if rates of CO_2 emission decline. In contrast, the "flow gas" CH_4 has an e-folding time of about 12 years and is removed from the atmosphere in a relatively short period of time. The climate impacts of cumulative pollutants such as CO_2 and short-lived climate pollutants (SLCP) such as CH_4 are often compared using Global Warming Potential (GWP), a metric that converts non-CO_2 GHG into CO_2-equivalent emissions. However, GWP has been criticized for overestimating the heating effects of declining SLCP emissions and conversely underestimating the heating impact of increasing SLCP emissions. Accurate quantification of the temperature effects of different CH_4 emissions scenarios is particularly important to fully understanding the climate impacts of animal agriculture, whose GHG emissions are dominated by CH_4.

Methods: A modified GWP metric known as Global Warming Potential Star (GWP*) has been developed to directly quantify the relationship between SLCP emissions and temperature change, which GWP cannot do. In this California dairy sector case study, we contrasted GWP- versus GWP*-based estimates of historical warming dynamics of enteric and manure CH_4 from lactating dairy cattle. We predicted future dairy CH_4 emissions under business-as-usual and reduction scenarios and modeled the warming effects of these various emission scenarios.

Results: We found that average CO_2 warming equivalent emissions given by GWP* were greater than those given by GWP under increasing annual CH_4 emissions rates, but were lower under decreasing CH_4 emissions rates. We also found that cumulative CO_2 warming equivalent emissions given by GWP* matched modeled warming driven by decreasing CH_4 emissions more accurately than those given by GWP.

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Discussion: These results suggest that GWP* may provide a more accurate tool for quantifying SLCP emissions in temperature goal and emissions reduction-specific policy contexts.

KEYWORDS

dairy production, methane, climate change, climate metrics, Global Warming Potential (GWP), enteric fermentation, manure management, short-lived climate pollutants

1. Introduction

CH_4 has the second greatest radiative forcing of all anthropogenic GHG after CO_2 (Myhre et al., 2013), and global CH_4 emissions, to which livestock is a major contributor, are responsible for about 0.5C of the 1.1C of human-forced global warming which has taken place since the year 1850 (IPCC, 2021). Enteric fermentation in the rumen of dairy cattle and their manure are major sources of biogenic methane (CH_4). Atmospheric CH_4 concentrations have increased by ∼150% since pre-industrial time (Gulev et al., 2021). Recent studies suggest that the increasing global CH_4 growth rate since 2007 has in part been driven by biogenic sources (Kai et al., 2011; Nisbet et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016).

CO_2 is known as a "cumulative pollutant" or "stock gas" due to its atmospheric lifetime that ranges from centuries to millennia (Pierrehumbert, 2014), causing it to accumulate in the atmosphere. CH_4, on the other hand, is known as a "short-lived climate pollutant" (SLCP) or "flow gas," and has an e-folding time of about 12 years. When both CO_2 and SLCP emissions increase over time, there is a short-term climate response to the change in radiative forcing ("transient warming"). When SLCP sources and sinks are equal, some long-term "equilibrium warming" will occur while the climate system equilibrates to past increases in SLCP emissions. However, after a sufficiently long period of constant emissions, there is no net accumulation in the atmosphere, radiative forcing of the atmospheric SLCP remains approximately constant, and SLCP-induced warming will stabilize. In contrast, CO_2-induced warming will always increase under positive CO_2 emissions (Cain et al., 2019). Because of its flow nature, a rapid reduction in methane emissions is one of the most feasible short-term measures to immediately curb global temperature rise (Ocko et al., 2021).

Climate metrics are used to "convert" annual emissions of various GHG that differ by atmospheric lifetime, radiative forcing, and relative magnitude of emissions into one common unit. One of the most widely used climate metrics is Global Warming Potential (GWP). GWP is constructed to estimate the radiative forcing of an emission pulse integrated over a given time horizon (often 20 or 100 years) relative to an equivalent pulse of CO_2. As constructed, GWP does not compare CO_2 to CH_4 emissions on the basis of equal radiative forcing, an accepted meaning of emissions equivalence within the radiative forcing framework, and therefore the meaning of emissions equivalence of CO_2 and CH_4 using GWP can be ambiguous (Wigley, 1998). GWP also does not relate radiative forcing to temperature change and as such is not able to capture temperature impacts within cumulative emission frameworks, although it is occasionally used for this purpose (Cui et al., 2017). GWP also does not differentiate between the contrasting behaviors of stock and flow gases, so GWP cannot capture the stable SLCP atmospheric concentrations that result from stable SLCP emissions rates. Because GWP treats SLCP like CO_2, which accumulates in the atmosphere even under stable emissions rates, GWP yields the wrong direction of temperature change under declining SLCP (Lynch et al., 2020). When CO_2 and CH_4 are compared specifically to assess their relative warming impacts on the climate, GWP overstates the warming impact of constant CH_4 emissions on global surface temperature by a factor of 3–4 over a 20-year time horizon, while understating the effect of a new CH_4 emission source by a factor of 4–5 over the 20 years following its introduction (Lynch et al., 2020). IPCC AR6 does not recommend any given emission metric because metric appropriateness depends on the purpose for which gases are being compared.

Abbreviations: E_{CH_4}, total annual CH_4 emissions (kg CH_4 per year); E_{EF}, annual enteric fermentation CH_4 emissions (kg CH_4 per year); E_{MM}, annual manure management CH_4 emissions (kg CH_4 per year); 3NOP, 3-nitrooxypropanol; AMMP, Alternative Manure Management Program; BAU, Business-as-usual; BAU EF, "business as usual" enteric fermentation scenario; CH_4, Methane; CO_2, carbon dioxide; CO_2eq, CO_2-equivalent emissions; CO_2we, CO_2-warming equivalent emissions; DDRDP, dairy digester research and development program; GHG, greenhouse gas; GWP, global warming potential; GWP*, global warming potential star; Man 40 plus BAU EF, manure management 40% reduction scenario added to the "business as usual" enteric fermentation (BAU EF) scenario; MMP, manure management practice; Pop_{dairy}, annual dairy cow population (head dairy cow); r, weight assigned to the rate-dependent warming effects of given SLCP in GWP*; RF_i, radiative forcing; s, weight assigned to the stock (long-term equilibration to past increases in forcing) contribution of given SLCP to GWP*; SLCP, short-lived climate pollutant; TCRE, transient climate response to cumulative carbon emissions; Tg, Teragrams, equivalent to million metric tons (MMT).

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Because livestock GHG emissions are predominately SLCP, the warming effects of livestock agriculture can be overestimated by GWP (Persson et al., 2015). The choice of the climate metric can change the estimated climate effect of CH_4, creating uncertainties in livestock contributions to global climate change and impacts of GHG mitigation in this sector (Reisinger et al., 2013). Thus, climate metrics designed to assess SLCPs more accurately are essential to quantify the warming impacts of animal agriculture, as well as husbandry factors that control these effects over time, such as increasing efficiency and decreasing herd size. In North America, decreasing dairy herd size and increasing production efficiency may have altered relative sizes of dairy GHG sources and sinks (Capper et al., 2009; Naranjo et al., 2020). California is the largest dairy producer in the United States (USDA National Agricultural Statistics Service, 2019), and in 2017, agricultural manure management was California's second largest source of CH_4. Dairy CH_4 emissions from cow manure in California are relatively high because flush water lagoon systems are the predominate manure management system on California dairies (CARB, 2022b), and anaerobic lagoons emit the most CH_4 per head of all common manure management practices (Owen and Silver, 2015). In 2016, the California Senate passed S.B. 1383, mandating a 40% reduction of dairy manure management CH_4 emissions from 2013 levels by 2030 (Lara, 2016). Thus, using a metric that can capture the flow nature of CH_4 will gain importance as agricultural CH_4 emissions reductions strategies are implemented, particularly those targeting emissions from dairy manure.

In response to potential misrepresentations of warming effects of SLCPs by GWP, an alternate metric, Global Warming Potential Star (GWP*) has been developed. GWP* is a recent and novel application of the commonly used climate metric GWP, designed to represent the flow gas properties of SLCP rather than treating them like cumulative stock gases such as CO_2. While applying GWP to annual emissions of non-CO_2 GHG gives emissions in units of "CO_2-equivalent emissions (CO_2eq)," GWP* gives emissions in "CO_2-warming equivalent emissions (CO_2we)." GWP* relates CO_2 pulses to SLCP emissions based on approximately equivalent radiative forcing of the emissions, so CO_2we are both directly comparable to CO_2eq and can be directly related to temperature change caused by these emissions (Smith et al., 2021), unlike GWP-based CO_2eq, as discussed above (Wigley, 1998). GWP* has been demonstrated to capture dynamics of SLCP-forced warming in datasets with global emissions across many economic sectors (Lynch et al., 2020). While some authors have debated the applicability of GWP*to national and sectoral emissions (Rogelj and Schleussner, 2019), the present study is the first to use GWP* to assess dairy CH_4 warming dynamics over time and to estimate warming impacts of the mandated CH_4 mitigation efforts in California using GWP vs. GWP*. While the objective of this study was not to provide a comprehensive inventory of all CH_4 emissions from California dairy production or a cradle-to-farm gate environmental impact analysis of the California dairy production system, the present study serves as a case study to assess GWP*'s ability to represent the warming effects of sectoral SLCP under declining emissions rates. It also serves as a characterization of potential drivers of these declining dairy CH_4 emissions in California. Our objectives were to compare GWP-based CO_2-equivalent emissions vs. GWP*-based CO_2-warming equivalent emissions calculated from historical California CH_4 emissions from lactating dairy cattle and to characterize dairy CH_4 warming dynamics from 1990 to 2017. We also aimed to compare the GWP- and GWP*-based dynamics of warming effects of dairy CH_4 under future business-as-usual and reduction emissions scenarios. We hypothesized that GWP*-based cumulative CO_2-warming equivalent emissions would decline under declining CH_4 emissions and would match the dynamics of CH_4's warming effects.

2. Methods

2.1. Estimating annual methane emissions from California dairy cattle

2.1.1. Calculation of historical methane emissions from California dairy cattle (1950–2017)

We calculated annual enteric fermentation and manure management CH_4 emissions from 1950 to 2017 based on the historical California dairy cow population and US EPA Greenhouse Gas Inventory Annex 3.10 (EPA, 2013a). "Annual" emissions refer to yearly CH_4 emissions estimates that have not been converted into CO_2-equivalent or CO_2-warming equivalent emissions. Total annual CH_4 emissions from California dairies were calculated using Equation 1:

$$E_{CH_4} = E_{EF} + E_{MM}$$

Where E_{CH_4} is total annual CH_4 emissions (kg CH_4 per year), E_{EF} is annual enteric fermentation CH_4 emissions (kg CH_4 per year), and E_{MM} is annual manure management CH_4 emissions (kg CH_4 per year).

Annual CH_4 emissions from enteric fermentation were calculated using Equation 2:

$$E_{EF} = Pop_{dairy} \times EF_{EF}$$

Where E_{EF} is annual enteric fermentation CH_4 emissions (kg CH_4 per year), Pop_{dairy} is annual lactating dairy cow population (head dairy cow) and EF_{EF} is annual enteric fermentation emission factor (kg CH_4 per head dairy cow per year).

Dairy cow populations were derived from California Department of Food and Agriculture (CDFA) Agricultural Resource Directory reports, which provided total dairy cattle population data by county (CDFA, 2000, 2007). Annual enteric CH_4 and manure CH_4 emission factors for California dairy cattle for 2000–2017 were obtained from the California Air Resources Board (CARB) Documentation of California's Greenhouse Gas Inventory (CARB, 2022a,b). The CDFA dairy cattle population data was assumed to represent only lactating cows, so we used the enteric fermentation CH_4 emission factor for lactating cows. Enteric CH_4 emissions factors are determined based on estimated gross energy (GE) intake and CH_4 conversion rate (Y_m), which is the fraction of GE in feed converted to CH_4. GE and Y_m depend on the animal's production demands, and the characteristics of the diet fed (EPA, 2013a). Manure CH_4 emissions factors are estimated by CARB using US EPA methodology (EPA, 2013b) and are based on typical animal mass, volatile solids excretion rate (portion of organic matter in the diet that was not digested by the animal and is thus available for use by methanogenic bacteria), maximum methane producing capacity of excreted volatile solids, and nitrogen excretion rate (CARB, 2022b). Because annual emission factors were unavailable before 2000, we used the 2000 emission factors for estimates from 1950 to 1999 (Supplementary Table S1). Annual CH_4 emissions from manure management (E_{MM}, kg CH_4 per year) were calculated for *i* different manure management practices (MMP) with emission factor EF_{MMPi} (kg CH_4 per cow, Supplementary Table S2) using Equation 3:

$$E_{MM} = Pop_{dairy} \times \left(\sum_{i=1}^{i} EF_{MMP_i} \times \frac{manure_{MMP_i}}{manure_{total}} \right)$$

The proportion of manure managed by each manure management system in California and the emissions factors for each management system were obtained from the Documentation of California's Greenhouse Gas Inventory (CARB, 2022b). Because MMP proportions before year 2000 were not available from CDFA, we used the 2000 manure management practice proportions and emissions factors for 1950–1999 (Supplementary Table S3).

2.1.2. Scenario analysis of methane emissions from California dairy cattle (2018–2029)

Business-as-usual ("BAU") future emissions scenarios were generated using the same methodology. We obtained projected California dairy cattle population for 2018 to 2029 from the 2020 U.S. Agricultural Market Outlook baseline report from the Agricultural Markets and Policy (AMAP) program at the University of Missouri (FAPRI and AMAP, 2020a), which provides projected dairy cattle population assuming current policies and macroeconomic conditions remain in place (FAPRI and AMAP, 2020b). The model includes behavioral supply equations that determine milk supply *via* dairy cow inventories and milk yield per cow on a state-level basis. Milk supply equations are driven by expected net returns, which are driven by applicable federal or state policy. Demand equations are specified as a function of price, relevant substitute product prices and consumer income for various milk products (Johnson et al., 1993; Westhoff and Brown, 1999; Blayney and Normile, 2004; Fabiosa et al., 2005). These dairy cattle population projections (Supplementary Table S4) have an average annual decline rate of 0.32%, which agrees with CARB estimates of 0.5% decline in dairy cattle population from 2017 onward (CARB, 2022c). We assumed all cows in the projected dairy cattle population were lactating. We used 2017 emission factors and MMPs to calculate emissions from these dairy cows and used these emissions to extend historical 1950–2017 emissions time series to 2029 under "business-as-usual," meaning with no methane reduction programs. We used 2017 emissions factors because projected emissions factors were not available. Enteric fermentation emissions factors used by CARB were the same from 2012 to 2017 (Supplementary Table S1). Furthermore, the same emissions factors have been used up to 2020, the most recent year of the CARB GHG emissions inventory (CARB, 2022a). Because CH_4 emissions factors are estimated based on dietary and production parameters, if regionally typical diets and production remain approximately the same over time, emissions factors will remain the same from year to year. Thus, without data on future dairy cattle enteric CH_4 emissions factors, we assumed that enteric fermentation CH_4 emissions per cow would remain stable through 2029. See Section 4.4 for further exploration of this assumption.

Because AMAP provided historical cattle population data that differed slightly from the CDFA population data used for annual CH_4 emissions, enteric fermentation and manure management CH_4 emissions estimates from both differed. Linear regression was used to relate enteric fermentation and manure management CH_4 emissions estimates based on historical AMAP and CDFA population values from years for which estimates for both were available, and then future emissions estimates based on AMAP population values were adjusted according to the regression relationship (see Supplementary Table S4 for further explanation).

We generated the "Manure 40" emissions reduction scenario following California Senate Bill No. 1383 which mandates the adoption of "regulations to reduce methane emissions from livestock manure management operations and dairy manure management operations, consistent with this section and the strategy, by up to 40 percent below the dairy sector's and livestock sector's 2013 levels by 2030" (Lara, 2016). This law requires reductions in manure management emissions and does not mandate reductions in enteric fermentation emissions, so the aggregated scenario "Manure 40 plus BAU EF" refers to the manure management 40% reduction scenario added to the "business as usual" enteric fermentation (BAU EF) scenario. We assumed the 40 percent reduction goal would be met by 2030 and assumed a constant rate of reduction to meet these goals from 2018 to 2030. Such reductions could potentially be achieved by converting manure management systems from high-CH_4 emitting anaerobic lagoons to alternative management systems; see Section 2.4. Methane emissions between 2017 and 2030 were interpolated with constant reduction rate; the difference between emissions in 2017 and 2030 was divided by 13 and this step value was added to each intervening year. We also generated the "3NOP" enteric fermentation reduction scenario using reductions from use of 3-nitroxypropanol (3NOP), a synthetic feed additive that inhibits the enzyme that catalyzes the methane-forming step in the rumen (Duin et al., 2016). Maximum reductions in enteric CH_4 emissions from dairy cattle supplemented with 3NOP vary across studies and may depend on animal factors and basal diet (Dijkstra et al., 2018). In the only dairy 3-NOP study conducted in California, maximum net reductions using 3NOP were 11.7% (Feng and Kebreab, 2020). We assumed this reduction would be achieved by 2030 and interpolated emissions of intervening years using the same method as manure management emissions. The "Manure 40 plus 3NOP" refers to the 40% manure management reduction scenario plus the 11.7% "3NOP" enteric fermentation reduction scenario.

2.2. Calculating CO_2-equivalent emissions using GWP and CO_2-warming equivalent emissions using GWP*

2.2.1. Converting annual CH_4 emissions to CO_2-equivalent emissions using GWP

In the following section, we describe how GWP and GWP* were used to calculate CO_2-equivalent (CO_2eq) or CO_2-warming equivalent emissions (CO_2we), respectively. GWP is generated by integrating the radiative forcing (the change in incoming and outgoing energy of the Earth system actuated by a given GHG) of a single emission ("pulse") of that GHG over a given time horizon H, divided by the same quantity for CO_2. The GWP of gas i with radiative forcing (RF_i) by Equation 4:

$$GWP_i = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{CO_2}(t)dt} \text{ (Solomon et al., 2007).}$$

GWP is used to convert other GHGs into CO_2eq, defined for a gas i as emissions per year (E_i) multiplied by GWP. CO_2eq are defined by Equation 5:

$$CO_2eq = E_i \times GWP_i.$$

Where CO_2eq are given in teragrams per year (Tg, equivalent to million metric tons, MMT) of CO_2eq emissions (TgCO_2eq/year) and E_i is given in Tg per year of gas E_i.

We used a 100-year time horizon for both GWP and GWP*. We used the GWP_{100}value of CH_4 from the IPCC 4th Assessment Report (Solomon et al., 2007), 25, which is consistent with the CARB GHG Current California Emission Inventory Data (CARB, 2022a,b).

2.2.2. Converting annual CH_4 emissions to CO_2-warming equivalent emissions using GWP*

We converted the CH_4 emissions into CO_2-warming equivalent emissions (CO_2we) using GWP*. GWP* considers an increase in the emission rate of an SLCP to be equivalent to a one-off pulse emission of CO_2 (Allen et al., 2018) and is used to convert SLCP emissions to CO_2we, which are directly comparable to CO_2eq (Allen et al., 2018). Under GWP*, CO_2we are defined by Equation 6:

$$CO_2we = GWP_i \times \left(r \times \frac{dE_i}{dt} \times H + s \times E_i \right)$$

where CO_2we are given in Tg of CO_2-warming equivalent emissions per year (TgCO_2we per year), GWP_i is the conventional GWP for gas i over time-horizon H, dE_i the change in the emission rate of gas i over the preceding dt years in Tg E_i per year, E_i the emissions of gas i in that year in Tg E_i per year, and r and s the weights assigned to the rate and stock contributions, respectively (Cain et al., 2019). r controls the rate-dependent warming effects of SLCP and s controls the long-term equilibration to past increases in forcing. We used $r = 0.75$ and $s = 0.25$ according to Cain et al. (2019), where these coefficients are the mean of coefficients determined when regressing different cumulative CH_4 emissions scenarios against modeled warming of these emission scenarios. We used a dt of 20 years according to Allen et al. (2018). Using $r = 0.75$, $s = 0.25$, $H = 100$, and $dt = 20$, the GWP* equation can be simplified further to Equation 7 (Lynch et al., 2020):

$$CO_2we = \left(4 \times E_{i_t} - 3.75 \times E_{i_{t-20}}\right) \times GWP_i.$$

We used this equation for conversion of annual CH_4 emissions into CO_2we emissions. It should be noted that the definition of GWP*-based CO_2-warming equivalent emissions has since been updated to include a scaling factor g ($g = 1.13$) to directly relate the radiative forcing of CO_2 and SLCP emissions without reference to temperature response, but the authors suggest that scaling factors of order 10% may not be necessary given their additional complexity (Smith et al., 2021).

2.3. Modeling warming responses to estimated methane emissions

We used the FaIR (Finite-Amplitude Impulse Response) v1.3 climate-carbon-cycle model to simulate the warming effects of the annual CH_4 emissions (Millar et al., 2017; Smith et al., 2018). It should be noted that this FaIR model is not the same as climate policy decision-support tool FAIR model (den Elzen and Lucas, 2005). Following Lynch et al. (2020), we forced the model with the complete RCP4.5 emissions scenario (Smith and Wigley, 2006; Wise et al., 2009; Lamarque et al., 2010), then forced the model with these same emissions, plus CH_4 emissions from each scenario. We then subtracted the first warming time-series from the second to generate the warming response to each emissions scenario. We used default FaIR parameters and set volcanic and solar forcing to zero and efficacies for each forcing agent compared to CO_2 to one, except black carbon, which was set to three (Bond et al., 2013).

2.4. Identifying husbandry factors driving declining dairy CH_4 emissions

Given the importance of capturing CH_4's flow nature especially under declining emissions rates, we conducted a separate analysis from that described in Sections 2.1–2.3 to determine if California dairy background CH_4 emissions are declining and identify husbandry factors driving potential decline. Production data (dairy cattle populations and per capita dairy cow milk production) were obtained from the USDA QuickStats database (USDA National Agricultural Statistics Service, 2019). Manure management CH_4 reductions from emissions reduction programs were obtained from the CDFA Dairy Digester Research and Development Program (DDRDP) and Alternative Manure Management Program (AMMP) websites (CDFA, 2022a,b). To investigate the impact of these programs, we estimated what CH_4 emissions would have hypothetically been without these programs. These estimates comprised a separate analysis and were not used to investigate emission dynamics or to force the climate model but were only used to assess the impact of various factors that may have led to reduced CH_4 emissions in California. To estimate hypothetical emissions without DDRDP and AMMP, annual emission reductions provided by CDFA were converted from Tg CO_2eq to Tg CH_4 using the AR4 GWP100 of CH_4 (25) and were added cumulatively to the estimated total annual dairy CH_4 emissions of the reduction year. For example, the 2016 estimated emissions reductions were added to 2016 CH_4 emissions to estimate hypothetical 2016 emissions without DDRDP or AMMP reductions, and 2016 plus 2017 estimated emissions reductions were added to 2017 CH_4 emissions to estimate putative 2017 emissions without DDRDP or AMMP reductions, etc. Although DDRDP and AMMP reductions were available to 2019, historical CH_4 emissions were only available to 2017, so the 2017 CH_4 emissions were used for all years following 2017. Statistical analysis for the entire study was conducted in R (R Core Team, 2020).

3. Results

3.1. Comparison of average annual CO_2eq and CO_2we from each scenario

We converted historical annual CH_4 emissions, a future business-as-usual CH_4 emission scenario, and two future reduction CH_4 emissions scenarios from California dairy cattle into CO_2-equivalent emissions or CO_2-warming equivalent emissions using the two different metrics GWP and GWP*, respectively. We used the conventional GWP and the novel GWP*, which is a modification of GWP that contains a term for the change in the rate of emission of SLCP such as methane. GWP gives CO_2-equivalent emissions (CO_2eq), while GWP* gives CO_2-warming equivalent emissions (CO_2we). "Total dairy emissions" were calculated using Equation 1. We used an emission-based climate model to predict the warming impacts of each annual CH_4 emissions scenario to compare the warming profiles against the dynamics of CO_2-equivalent emissions calculated by each metric for each scenario.

We first investigated if GWP-based emissions estimates (CO_2eq) and GWP*-based emissions estimates (CO_2we) differed significantly in each emissions scenario. GWP-based CO_2eq emissions and GWP*-based CO_2we were calculated from identical annual "background" CH_4 emissions, but all average CO_2eq and CO_2we under the same reduction scenarios differed significantly (Figure 1). Average GWP*-based estimates for the historical period were larger than GWP-based estimates. In this historical period, there are 37% more annual CO_2-warming equivalent CH_4 emissions when calculated using GWP* than when calculated using GWP (Figure 1).

In the BAU manure and enteric CH_4 scenario and 40% reduction of manure management CH_4 with BAU enteric CH_4 scenario, CO_2we were lower than CO_2eq (Figure 1). Furthermore, under 40% reduction of future annual manure management CH_4 emissions in the "Man. 40 plus BAU EF CO2eq" reduction scenario, some annual CO_2we are negative, while CO_2eq were never negative. Under 40% reduction of future annual manure management CH_4 emissions with maximum 3NOP reductions, the average of *all* annual CO_2we were negative, while again CO_2eq were never negative (Figure 1).

CO_2eq are less variable than GWP*-based CO_2 warming equivalent emissions, particularly in the future BAU scenario, where CO_2eq are approximately constant. GWP*-derived emissions are more variable because they are calculated by

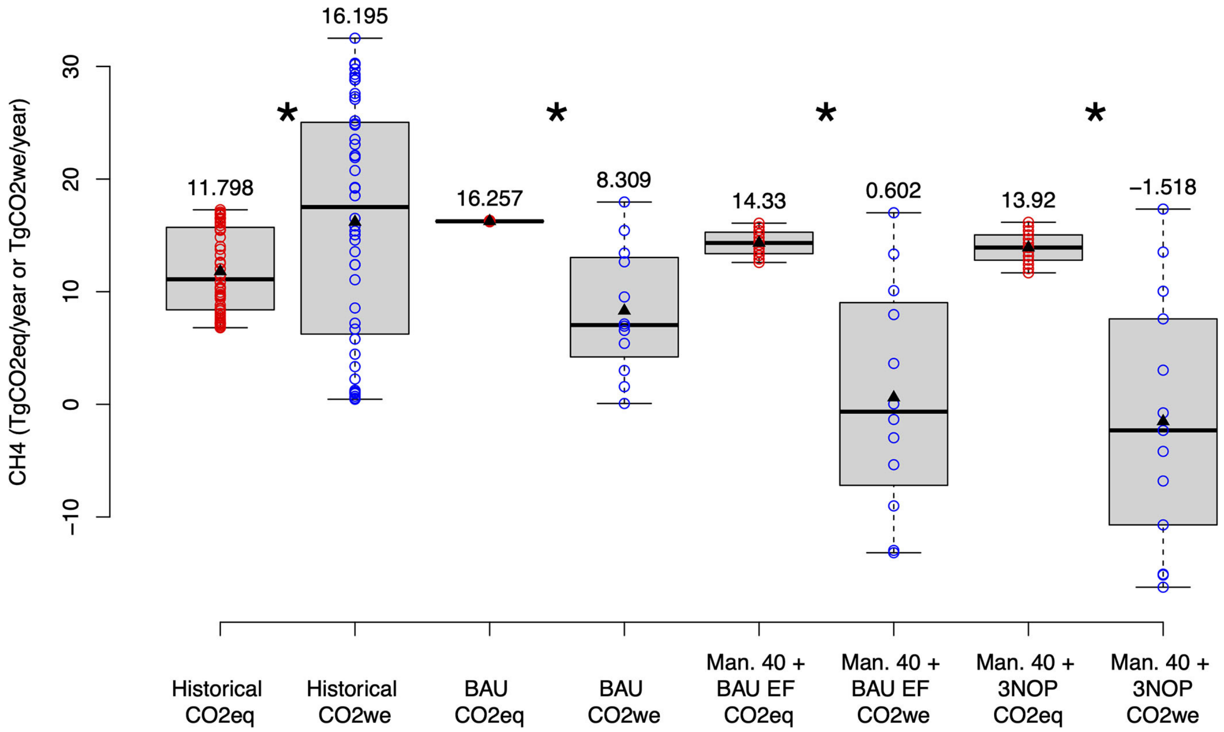

FIGURE 1
Comparison of annual total dairy CH_4 emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively. The *x*-axis shows each emission scenario and which metric was used. Historical data is from 1950 to 2017. The BAU scenario and Manure 40 plus BAU EF ("Man. 40 + BAU EF") are from 2018 to 2029. The Manure 40 plus 3NOP ("Man. 40 + 3NOP") is from 2018 to 2030. The *y*-axis denotes CO_2-equivalent or CO_2-warming equivalent emissions, respectively, computed from CH_4 emissions; GWP gives "CO_2eq" emissions, while GWP* gives "CO_2we." Each circle represents an observation of annual emissions rate from each time period and emissions scenario. Red open circles are data points calculated using GWP; blue open circles are data points calculated using GWP*. Values above boxes are mean values; means are denoted as black triangles on plot. Asterisks between plots indicate means of GWP- and GWP*-based emissions differ significantly (paired student's *t*-test, $p < 0.05$).

subtracting the current year emissions rate from that of 20 years previously, which is particularly variable under reduction scenarios where future emissions are reduced relative to those in the historical period.

3.2. Comparison of cumulative CO_2eq and CO_2we with modeled warming over historical period (1950–2017)

Because cumulative CO_2 emissions and temperature change are linearly related (Allen et al., 2009; Matthews et al., 2009), the dynamics of the two should be similar over time and the warming profile serves as a means of evaluating GWP and GWP*. We next examined the relationship between "background" annual CH_4 emissions, cumulative GWP- and GWP*-based emissions estimates, and modeled warming, in each emissions scenario, to evaluate these two metrics.

In the historical period, annual CH_4 emissions increased from 1950 to 2008, but slightly decreased from 2008 to 2017 (Figure 2A). During the increasing annual CH_4 emissions, CO_2we were higher than CO_2eq (Figure 2B). Under decreasing annual CH_4 emissions from 2008 to 2017, however, annual CO_2we decreased, while annual CO_2eq increased. Because annual CO_2we decreased from 2008 to 2017, when each annual estimate was added up to give cumulative emissions, cumulative CO_2we did not increase linearly from 2008 to 2017 but instead, the rate of increase of cumulative emissions slowed, decreasing the slope of the line (Figure 2C). In contrast, because annual CO_2eq increased over the entire historical period, cumulative CO_2eq increased linearly (Figure 2C). The slope of the line representing warming caused by annual CH_4 emissions also decreased from 2008 to 2017 (Figure 2C). As noted above, the dynamics of cumulative CO_2-equivalent emissions and warming forced by these emissions should be similar over time, so in this scenario, the decreasing slope of the warming and cumulative GWP* lines suggests that they may be in better agreement than GWP and the warming line.

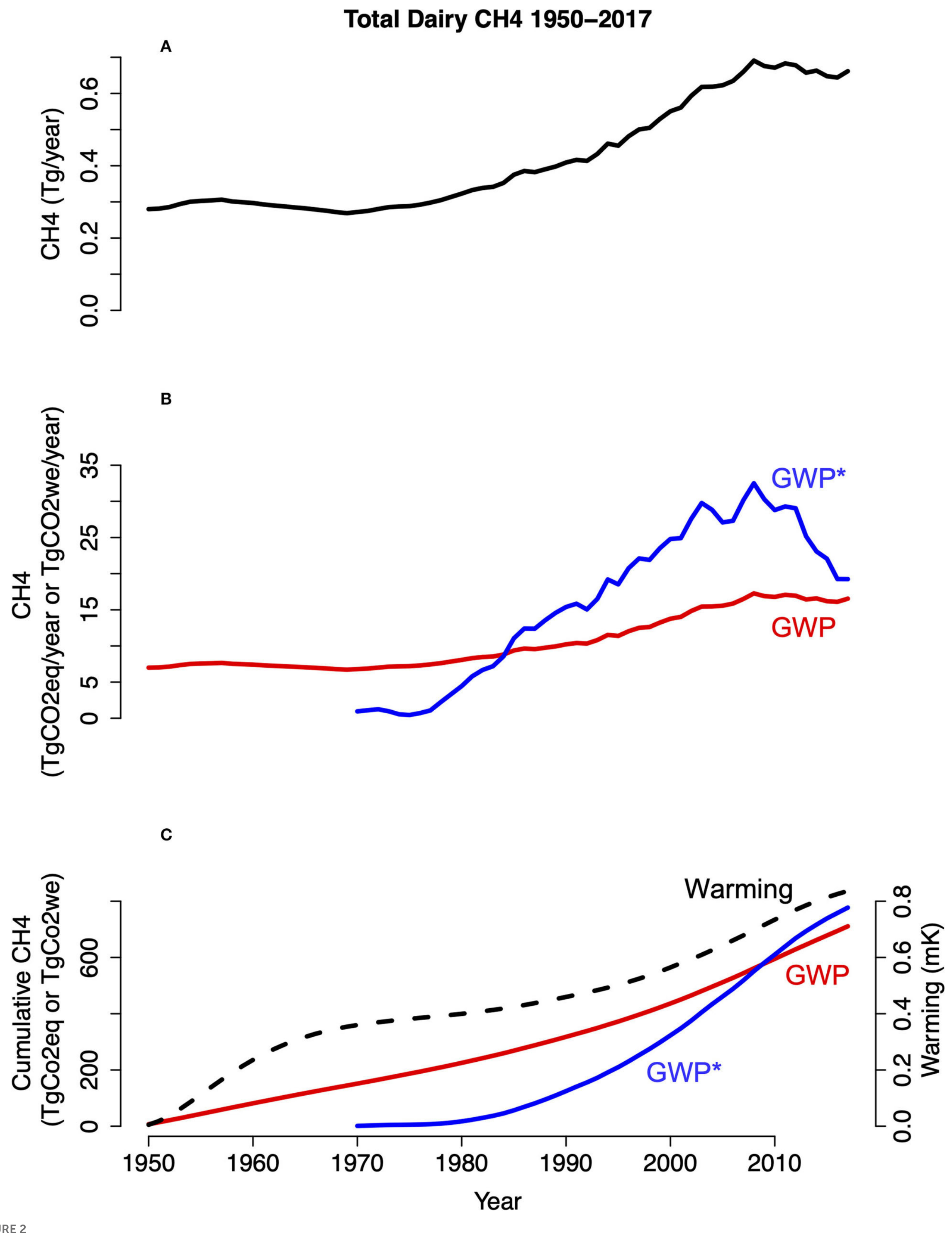

FIGURE 2
California 1950–2017 total historical CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years and the *y*-axis represents annual CH_4 emissions **(A)**, annual CO_2eq or CO_2we **(B)**, or cumulative CO_2eq or CO_2we **(C)**. CO_2we are represented in **(B, C)** by the blue solid line ("GWP*"), GWP-based CO_2eq are represented by the red solid line ("GWP"), and temperature is given in **(C)** by the dashed black line ("Warming"). The temperature axis in **(C)** is scaled by 0.001 mK/TgCO_2, or 1 K/TtCO_2. The scaling factor that relates cumulative CO_2 emissions to temperature change is known as transient climate response to cumulative carbon emissions (TCRE). The scaling factor here (approximate TCRE) exceeds the IPCC likely range, likely due to a large increase in annual CH_4 emissions in the 1950s leading to a larger GWP of CH_4 in this period (see Section 4). This large GWP may be responsible for the "bulge" in warming between 1950 and 1990 **(C)**.

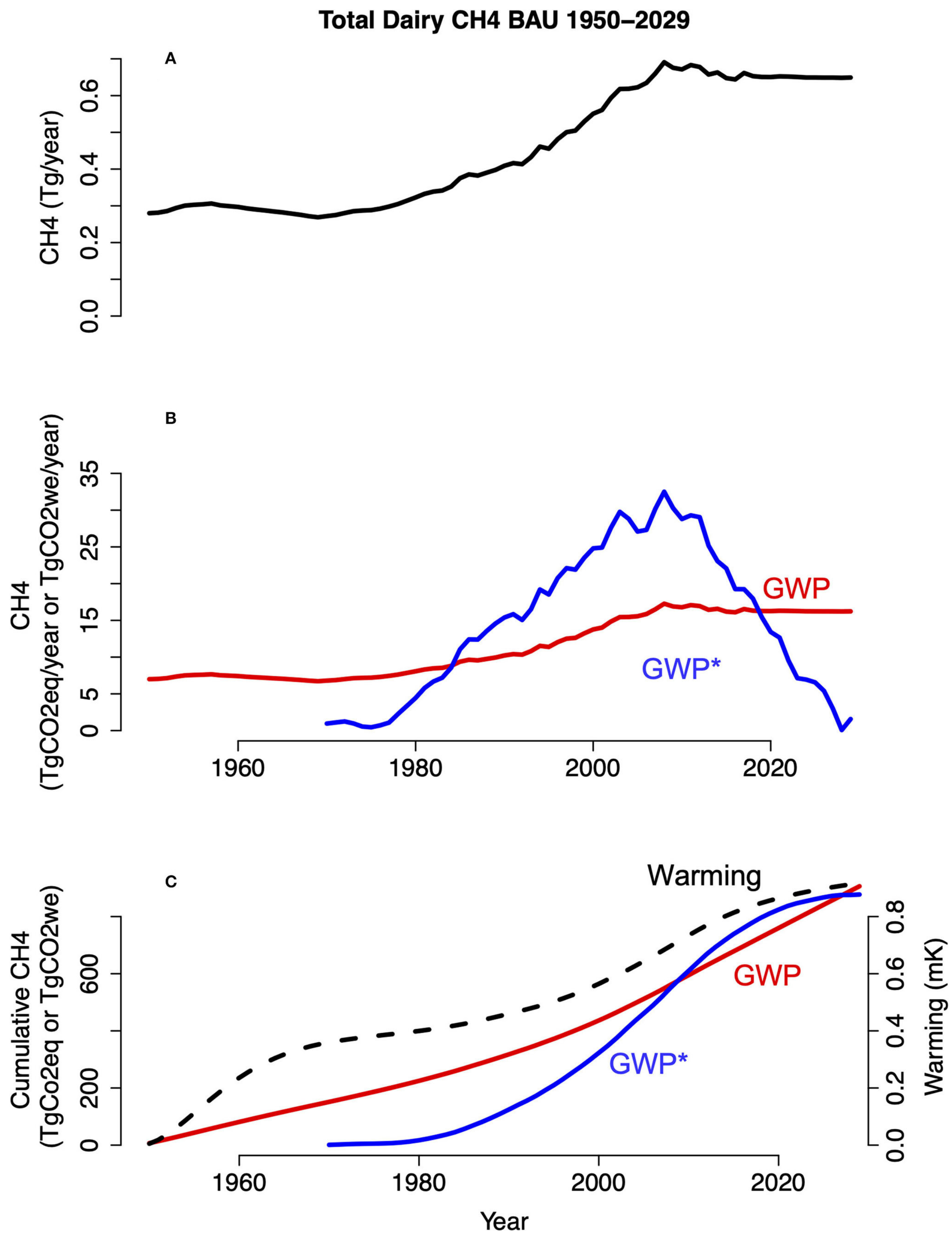

FIGURE 3
California future BAU total (enteric fermentation plus manure management) CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years and the *y*-axis represents annual CH_4 emissions **(A)**, annual CO_2eq or CO_2we **(B)**, or cumulative CO_2eq or CO_2we **(C)**. CO_2we are represented in **(B, C)** by the blue solid line ("GWP*"), CO_2eq are represented by the red solid line ("GWP"), and temperature is given in **(C)** by the dashed black line ("Warming"). The temperature axis **(C)** is scaled by 0.001 mK/TgCO_2, or 1 K/TtCO_2, as in Figure 2.

3.3. Comparison of cumulative CO_2eq and CO_2we with modeled warming over BAU scenario (2017–2029)

In the BAU manure and enteric CH_4 emissions scenario, annual background CH_4 emissions from 2008 to 2029 were approximately constant (Figure 3A). Under constant annual CH_4 emissions, CO_2we declined, while CO_2eq were approximately constant (Figure 3B).

Because annual CO_2we decreased from 2008 to 2017, when each annual estimate was added up to give cumulative emissions, cumulative CO_2we did not increase linearly from 2008 to 2017 but instead, the rate of increase of cumulative emissions slowed and the line representing CO_2we "flattens out," or stops accumulating (Figure 3C). In contrast, because annual CO_2eq increased over the entire historical period, cumulative CO_2eq increased linearly (Figure 3C).

Because GWP*-based cumulative CO_2we did not increase under constant annual CH_4 emissions, they fit the warming better than CO_2eq, like in the historical period, but the difference in the near-constant BAU scenario is easier to see. GWP-derived estimates did not match warming dynamics because CO_2eq continued to increase linearly under constant annual CH_4 emissions.

3.4. Comparison of cumulative CO_2eq and CO_2we with modeled warming over 40% manure CH_4 emissions reduction plus BAU enteric CH_4 emissions scenario (2017–2029)

In the "Manure 40 plus BAU EF" reduction scenario, manure CH_4 is reduced by 40% from 2017 to 2029, while enteric CH_4 follows a "business as usual" projection. In this moderate reduction scenario, annual background manure management and total CH_4 emissions declined from 2017 to 2029 (Figures 4A, B). Under declining CH_4 emissions from 2017 to 2029, both manure management and total CO_2we declined, even reaching negative annual emissions rates (Figures 4C, D). CO_2eq also declined under declining annual CH_4 emissions, but did not reach negative emissions rates.

When each annual CO_2we emissions estimate was added up to give cumulative emissions, because some annual emissions rates were negative, cumulative CO_2we *decreased* from 2017 to 2029 (Figures 4E, F). In contrast, GWP-based cumulative CO_2eq continued to increase under declining future annual CH_4 emissions (Figures 4C, D). Warming forced by declining annual CH_4 emissions also declined, so cumulative GWP*-based CO_2we reflected these dynamics better than cumulative GWP-based CO_2eq.

3.5. Comparison of cumulative CO_2eq and CO_2we with modeled warming over 40% manure CH_4 emissions reduction plus reduced enteric CH_4 emissions scenario (2017–2030)

The "Manure 40 plus 3NOP" reduction scenario represents a more ambitious reduction scenario than "Manure 40 plus BAU EF," because it incorporates reductions in both manure and enteric CH_4. In this high reduction scenario, future annual enteric fermentation and total CH_4 emissions declined from 2017 to 2030 (Figures 5A, B). This decline also occurred in the "Manure 40 plus BAU EF," but the decrease is sharper in the "Manure 40 plus 3NOP" scenario. Under declining future CH_4 emissions, both enteric fermentation and total CO_2we declined and reached negative annual emissions rates (Figures 5C, D). CO_2eq also declined under declining annual CH_4 emissions, but did not reach negative emissions rates.

Again, when each annual CO_2we emissions estimate was added up to give cumulative emissions, because some annual emissions rates were negative, cumulative CO_2we *decreased* from 2017 to 2030 (Figures 5E, F). In contrast, GWP-based cumulative CO_2eq continued to increase under declining future annual CH_4 emissions (Figures 5C, D). Warming forced by declining annual CH_4 emissions also declined, so cumulative GWP*-based CO_2we reflected these dynamics better than cumulative GWP-based CO_2eq. Because the rate of decline of emissions is greatest in this scenario, the difference between GWP- and GWP*-based emissions estimates and their agreement with warming dynamics is most clear in this scenario.

3.6. Relationship between cumulative CO_2eq and CO_2we from all scenarios and modeled warming

Figure 6 plots cumulative CO_2eq and CO_2we from historical, BAU, and reductions scenarios, respectively, against modeled warming. This plot shows the same information as previous plots, but allows us to directly visualize the relationship between cumulative CO_2 emissions and temperature change in this study. We expect cumulative CO_2 or CO_2-equivalent emissions and temperature to be linearly related, as this is a well-established physical relationship. In the historical period, annual background CH_4 emissions increased over time, and so both cumulative GWP-based CO_2eq and GWP*-based CO_2we increased, as discussed in Section 3.2. Modeled temperature also increased over time in the historical periods, as expected given the linear relationship between cumulative CO_2 emissions and temperature change (Figure 6A).

Under the "Manure 40 plus 3NOP" future reductions scenario, annual background CH_4 emissions decrease over

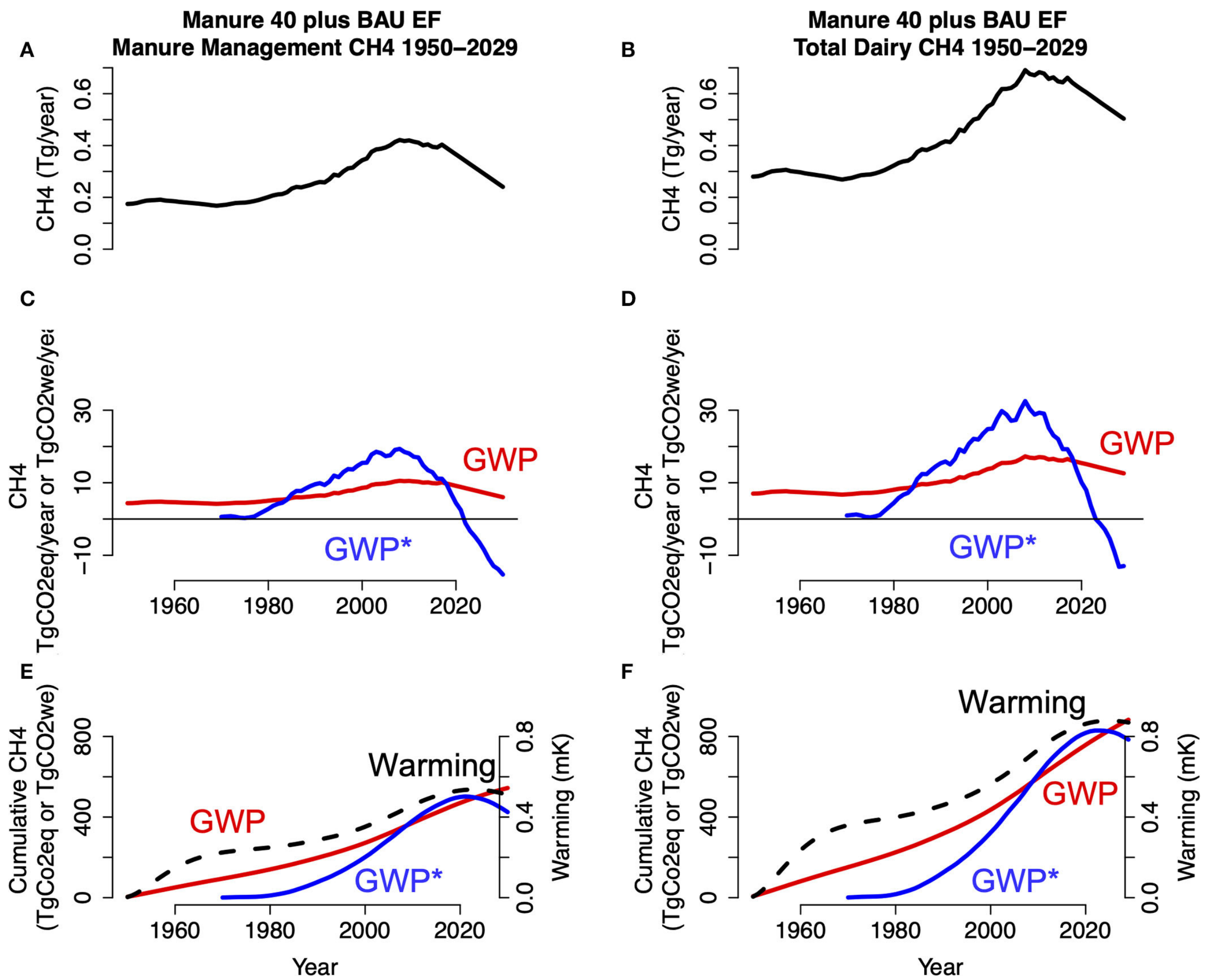

FIGURE 4

California future manure management and total "Manure 40 plus BAU EF" reduction scenario CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years, and the *y*-axis represents annual CH_4 emissions **(A, B)**, annual CO_2eq or CO_2we **(C, D)**, and cumulative CO_2eq or CO_2we **(E, F)**. Manure management CH_4 is presented in **(A, C, E)**, and total dairy CH_4 is given by **(B, D, F)**. CO_2we are represented in **(C–F)** by the blue solid line ("GWP*"), CO_2eq are represented in **(C–F)** by the red solid line ("GWP"), and temperature is given in **(E, F)** by the dashed black line ("Warming"). The temperature axis **(C)** is scaled by 0.001 mK/TgCO_2, or 1 K/TtCO_2, as in previous figures. The horizontal black line in **(C, D)** is at $y = 0$.

time. As discussed in Section 3.5, in this scenario, cumulative CO_2eq continue to increase in this scenario while cumulative CO_2we increased until 2017, then decreased. Temperature change forced by the background CH_4 emissions also increased until 2017, then decreased. That cumulative CO_2eq continue to increase implies that increasing cumulative emissions can cause decrease warming, which is an unphysical relationship (Figure 6B). In contrast, the relationship between cumulative CO_2we and warming is always linear—when cumulative CO_2we increase, warming is also increasing, but when CO_2we begin to decrease, warming also decreases and the blue line "turns back" on itself. This plot thus gives another visualization of results from previous plots, which are that CO_2we matched the dynamics of warming from declining background CH_4 emissions better than GWP-based emissions, or in other words can capture the physical relationship linking cumulative CO_2 emissions and temperature change that GWP does not.

In the manure and enteric CH_4 BAU scenario, annual background CH_4 emissions are approximately constant, as discussed in Section 3.3. Warming forced by these emissions "flatten out" during the period of constant background emissions. In this scenario, cumulative CO_2we "flatten out" and stop accumulating, while cumulative CO_2eq continue to increase. When cumulative CO_2eq are plotted against temperature change, while warming stays approximately constant, cumulative emissions continue to increase, implying that constant cumulative emissions can cause constant warming, which is an unphysical relationship (Figure 6B). In contrast, cumulative CO_2we stop increasing under these near-constant background emissions, almost "turning back"

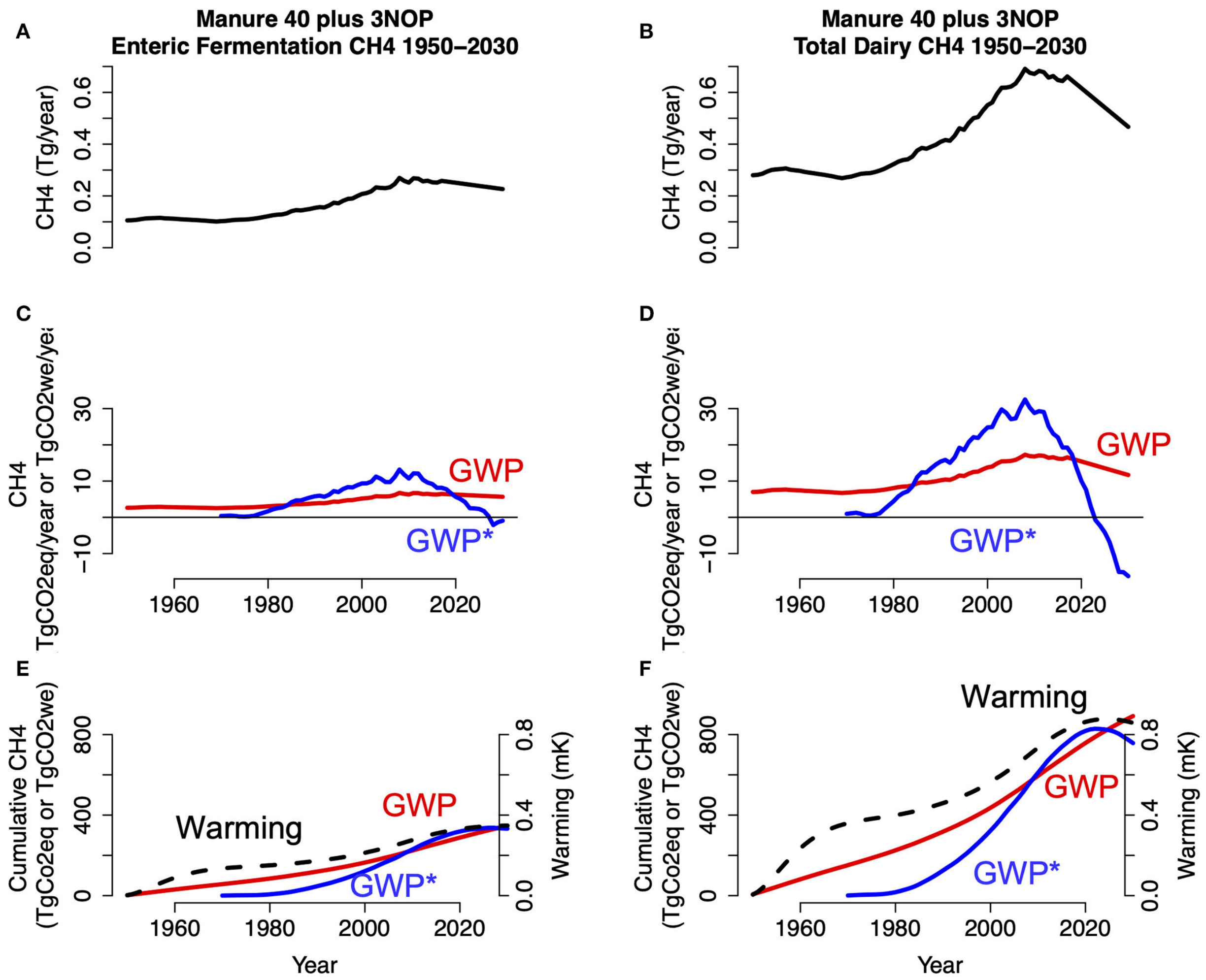

FIGURE 5
California future enteric fermentation and total "Manure 40 plus 3NOP" reduction scenario CH_4 emissions, comparison of these emissions converted to CO_2eq and CO_2we using GWP and GWP*, respectively, and cumulative CO_2eq and CO_2we with emissions-forced warming. The *x*-axis represents years, and the *y*-axis represents annual CH_4 emissions **(A, B)**, annual CO_2eq or CO_2we **(C, D)**, or cumulative CO_2eq or CO_2we **(E, F)**. Enteric fermentation estimates are given by **(A, C, E)**, and total dairy emissions are given by **(B, D, F)**. CO_2we are represented in **(C–F)** by the blue solid line ("GWP*), CO_2eq are represented in **(C–F)** by the red solid line ("GWP"), and temperature is given in **(E, F)** by the dashed black line ("Warming"). The temperature axis **(C)** is scaled by 0.001 mK/$TgCO_2$, or 1 K/$TtCO_2$, as in previous figures. The horizontal black line in **(C, D)** is at $y = 0$.

like in Panel C and again showing that GWP*-based emissions dynamics match warming dynamics better under constant background emissions.

3.7. Husbandry factors driving declining California dairy CH_4 emissions from 2008 to 2017

Given the importance of capturing CH_4's flow nature especially under declining emissions rates, we conducted a separate analysis from the hypothetical scenarios, including hypothetical reductions scenarios, giving the results described in Sections 3.1–3.6. We conducted this separate analysis to determine if California dairy background CH_4 emissions are in fact declining and, if so, to identify husbandry factors driving the decline in emissions. Historical annual CH_4 emissions decrease from 2008 to 2017 after a peak in 2008 (Figures 7A, B). This decrease in CH_4 emissions is likely a result of decreasing California dairy cattle populations, which peaked in 2009 (Figures 7A, C). Because CH_4 emissions depend heavily on cattle population, this decreasing population from 2009 to 2019 is likely driving decreasing CH_4 emissions. This decreasing cattle population in turn may be driven by increasing

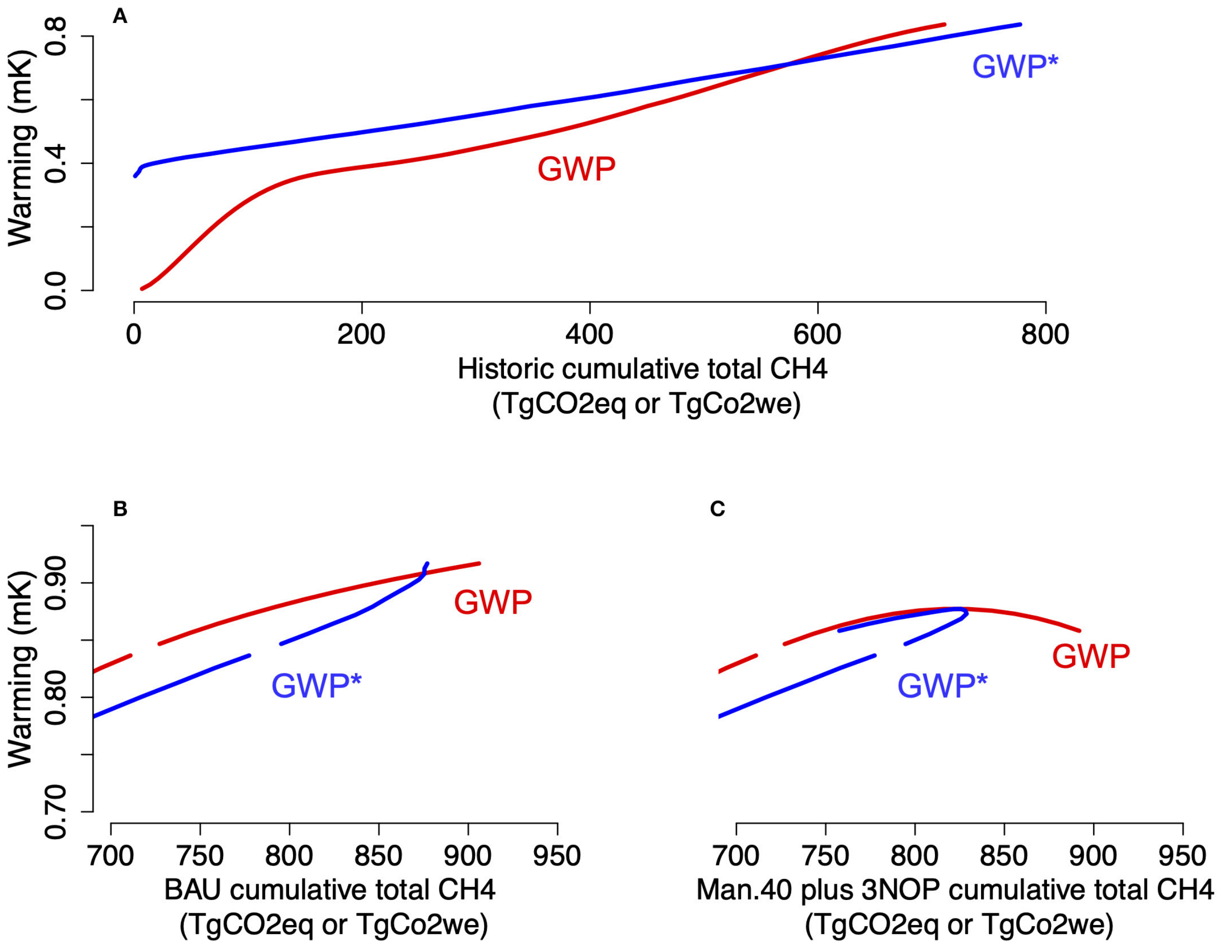

FIGURE 6
The relationship of CO_2eq and CO_2we with modeled warming response to these emissions. The *x*-axis shows cumulative CO_2eq calculated using GWP in red ("GWP"), or CO_2we calculated using GWP* in blue ("GWP*"). The y axis shows warming from annual CH_4. **(A)** Shows data from the historical (1950–2017) period. The slope of the line of cumulative CO_2 emissions and temperature change is approximately TCRE. **(B)** Shows future (2018–2029) BAU emissions, while **(C)** shows future (2018–2030) "Manure 40 plus 3NOP" reduction scenario emissions. Lines are broken between historical and future data.

per capita milk production (Figure 7C), as per capita milk production has increased from 2009 to 2019 and per capita milk production and dairy population are negatively correlated from 2009 to 2019 (data not shown). Manure management CH_4 emissions have also been reduced by CDFA Dairy Digester Research and Development Program (DDRDP) since 2015 and Alternate Manure Management Program (AMMP) since 2017. The majority of reductions are due to DDRDP. These programs provide estimates of annual CH_4 reductions due to program implementation, which have been added to historical annual CH_4 emissions to plot putative emissions without these programs. Decreases in total CH_4 since 2008 have been driven by decreasing population and decreased CH_4 from manure management due to CDFA programs (Figure 7B).

4. Discussion

4.1. Application of GWP* to CH_4 emissions from livestock agriculture

Previous studies have applied GWP* to large, RCP-based CH_4 datasets (Cain et al., 2019; Lynch et al., 2020). Ours builds upon this work and is the first to our knowledge to apply GWP* to sectoral emissions from a North American animal production system, and thus serves as case study for the application of GWP* to smaller industry- and locale-specific CH_4 emissions data. Previous authors have debated GWP*'s applicability to sectoral and national emissions, which will be discussed further here. Nonetheless, previous authors have applied GWP* and other alternative GHG metrics to local

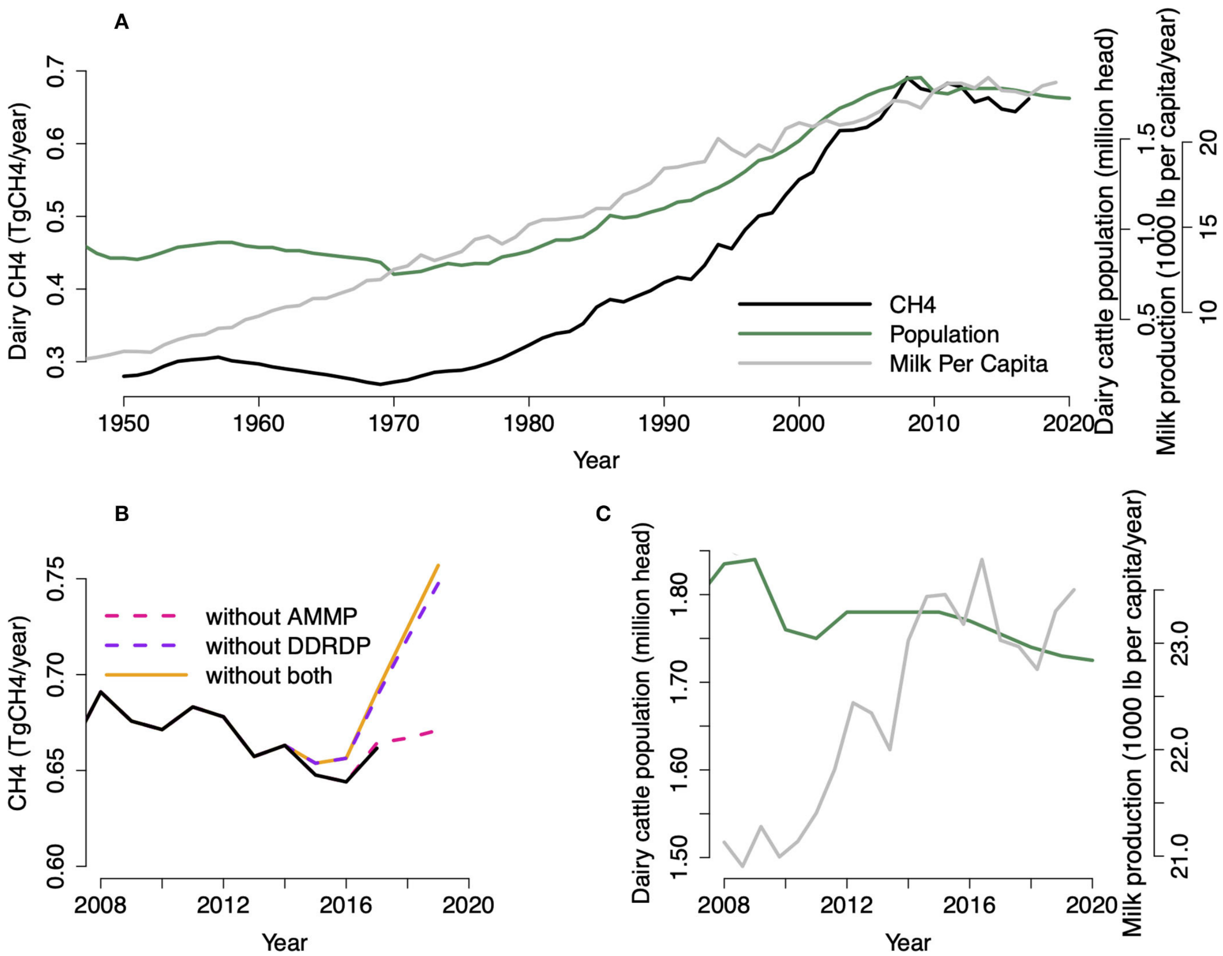

FIGURE 7
Mechanisms of decreasing CH_4 emissions since 2008 include decreasing dairy herd size, increasing per capita production, and manure management CH_4 reductions programs. In **(A–C)**, the *x*-axis shows years; in **(A)** the entire historical time series is shown (1950–2017), while in **(B, C)**, only 2008–2017 are shown. In **(A, B)**, the *y*-axis is annual total dairy CH_4 emissions, but in **(B)** the *y*-axis does not begin at zero in order to provide a close-up view of CH_4 dynamics from 2008 to 2017. In **(A)**, the right y axis shows per capita milk production and cattle population. **(B)** Shows hypothetical estimates of annual CH_4 reductions due to DDRDP and AMMP program implementation, which has been added to historical CH_4 emissions to plot putative emissions without these programs. The *y*-axis of **(C)** shows cattle population and the right y axis shows per capita milk production.

agricultural sectors, including Australian beef feedlots (Ridoutt et al., 2022), Australian sheep meat production (Ridoutt, 2021a), Australian livestock production (Ridoutt, 2021b), and Austrian dairy production (Hörtenhuber et al., 2022). Similar to reductions scenarios in our study, Ridoutt and coauthors found larger potential GHG reduction benefits from supplementing Australian beef steers with enteric CH_4-inhibiting macroalgae *Asparagopsis taxiformis* when emissions were assessed using GWP* rather than GWP (Ridoutt et al., 2022). Similarly to our study, Hörtenhuber and coauthors found that decreasing lactating dairy cattle population due to improved production efficiency resulted in strong sectoral emission reductions from dairy production, which were greater when assessed with GWP* than with GWP_{100} (Hörtenhuber et al., 2022). In Australian livestock industries where CH_4 emissions increased from 1990 to 2018 (beef, pork, and dairy production), emissions from the beef cattle, pig meat and milk production industries assessed using GWP* contributed to climate warming less than when assessed with the GWP_{100} climate metric (Ridoutt, 2021b). While increasing background emissions in Australia from 1990 to 2018 are similar to our "historical" scenario, we found that under increasing background emissions, GWP*-based emissions estimates were greater than those given by GWP. This discrepancy may be because the authors used total GHG emissions, not only CH_4, in their analysis. It may also result from annual Australian CH_4 emissions increasing by less than needed for CO_2we to exceed CO_2eq, 1% per year. In this study, dairy CH_4 emissions were 214 kt in 1990 and 275 kt in 2018, which gives an approximate rate of increase of 1% per year. Beef CH_4 emissions were 1,252 kt in 1990 and 1,421 in 2018, which gives an approximate rate of increase of 0.4% per year, below the approximate threshold for CO_2we greater than CO_2eq, discussed further immediately below.

4.2. Rate of change of CH_4 emissions leading to zero CO_2we emissions

Because of how the metrics are constructed, under a positive rate of change, CO_2we are greater than GWP-based CO_2-equivalent emissions when the rate of change of emissions is >1% per year. In our historical CH_4 emissions dataset, annual CH_4 emissions increased over time, leading to continuously increasing CO_2we. CO_2we are weighted heavily under increasing annual CH_4 emissions because CH_4 is being added to the atmosphere and CH_4 has a stronger radiative forcing per unit mass than CO_2 (Fuglestvedt et al., 2003). When CO_2eq are set equal to CO_2we (Equations 5 and 6), we see that $\frac{dE_i}{dt}$ is equal to E_i when $\frac{dE_i}{dt} = 0.01 \times E_i$. Thus, CO_2we will exceed CO_2eq when the rate of change of emissions is >1% per year, as noted by Lynch et al. (2020). The difference between CO_2eq and CO_2we suggests that GWP may underestimate, or that GWP* may overestimate, the relative strength of CH_4 to CO_2 under increasing annual CH_4 emissions in the near term after a pulse emission, and that GWP may overestimate them in the long term, as was also found in studies using idealized (e.g., hypothetical, as opposed to historical) CH_4 emissions (Lynch et al., 2020).

Because CH_4 is a flow pollutant, under constant annual CH_4 emissions the rate of generation and removal of CH_4 are approximately equal over the atmospheric lifetime of CH_4 and there is no net accumulation of CH_4. To demonstrate that GWP* can capture this short-lived behavior, Lynch et al. (2020) simulated a step increase to a sustained emission of CH_4, and found that over the first 20 years, CO_2we given by GWP* exceeded emissions given by conventional GWP. After the first 20 years, however, the rate of change of CH_4 emissions is 0, and the only CH_4 emissions are those represented by the "stock" or s term (Cain et al., 2019). At the same time, GWP-derived emissions remain above zero with constant annual CH_4 emissions which represents the behavior of a stock gas like CO_2. Similarly, in our BAU scenario under approximately constant annual CH_4 emissions, CO_2eq remain constant, while CO_2we fall almost to zero except for the contribution of the stock term (Figure 3).

4.3. Linking cumulative CO_2we with temperature change

Under decreasing annual CH_4 emissions rates, more CH_4 will have been removed from the atmosphere than is produced to replace it, and negative annual CO_2we emissions suggest negative warming relative to the reference year in our study. Annual CO_2eq under decreasing annual CH_4 emissions, however, were never negative in our study or in that of Lynch et al. (2020).

In the present study, cumulative (annual emissions summed over time) CO_2we dynamics over time match those of warming, which also decrease under decreasing annual CH_4 emissions. Lynch et al. (2020) found that under declining CH_4 emissions, CO_2we were negative, and the temperature effect forced by these declining CH_4 emissions was less positive, like turning down a thermostat (note that any positive CH_4 emissions are still very strong warmers of the climate). In contrast, under declining annual CH_4 emissions, CO_2eq continued to accumulate, and GWP did not indicate the correct direction of temperature change. Thus, warming profiles confirm that GWP*-based cumulative CO_2-warming equivalent emissions are able to represent the warming effects of CH_4 on the climate. Zhang et al. (2018) found that under declining SLCP emissions in the RCP 42.6 and 4.5 emission scenarios, effective radiative forcing from SLCP was negative. Cain et al. (2019) and Lynch et al. (2020) concluded that GWP* captures the fundamentally different behavior of short- vs. long-lived climate pollutants, especially under declining CH_4 emissions, and therefore provides a reliable metric to directly link greenhouse gas emissions to warming.

Due to their linear relationship, cumulative CO_2 emissions can be linked to global temperature change with a coefficient known as the Transient Climate Response to Cumulative Carbon Emissions (TCRE). Cumulative CO_2we should result in global temperature change when multiplied by this constant, and this constant is approximately the slope of a line when cumulative emissions and warming are plotted against each other. Given the similar dynamics of warming and cumulative emissions over time, cumulative emissions could simply be multiplied by a constant, which was ~0.001 mK/Tg CO_2, or 1 K/Tt CO_2, to give temperature change. GWP-based estimates, however, could not be linked to temperature changed simply using a coefficient because cumulative CO_2eq had different dynamics over time than warming. Like Cain et al. (2019) we also found that GWP*-based estimates plotted against temperature change resulted in a straight line, while GWP-based estimates did not. We found this line had an approximate slope of 1 K/Tt CO_2. The approximate change in temperature per unit cumulative CO_2 emissions that we found, 1 K/Tt CO_2, exceeds the IPCC likely range, possibly due to a large increase in annual CH_4 emissions in the 1950s leading to a larger GWP of CH_4 in this time period (Reisinger et al., 2011). The largest discrepancy between the dynamics of GWP*-based estimates and warming is during the period from 1950 to 1980, where a "bulge" occurred, possibly due to this increased GWP of CH_4.

Using Equation 6 and setting CO_2we to zero, Cain et al. (2019), found the rate of CH_4 emission that is equivalent to zero CO_2we and thus to approximately stable temperatures over the time period Δt. With $r = 0.75$, $s = 0.25$, and $H = 100$ years, as used in the present study (following Cain et al., 2019), 0.3% is the rate of decline of CH_4 emissions ($\Delta E/\Delta t$) under which CH_4-induced warming is stable. Under the "Manure 40 plus 3NOP" reduction scenario in the present study, the annual rate of decline of total CH_4 emissions from 2017 to 2030 is about 1.15%, while under "Manure 40 plus BAU EF," the rate of decline of total CH_4 emissions is about 0.92%. Thus, under future SB 1383-mandated emissions reductions, California dairy CH_4 emissions will warm the climate less than they do without these reductions, even under scenarios that limit manure management CH_4 emissions reductions only. The rate of decline of historical CH_4 emissions from the peak in 2008 to 2017, was 3.26%, a decline which we suggest has been driven by declining California dairy herd size driven by increasing per capita milk production, as well as by the CDFA DDRDP after its introduction in 2015, with a minor contribution from AMMP. Thus, under their current and predicted rates of reduction, California dairy CH_4 emissions will be below the level at which stable warming effect will be actuated by these emissions and will reduce warming vs. 20 years ago. This behavior contrasts with CO_2, whose atmospheric concentrations and radiative forcing increase even under decreased emissions rates.

4.4. Contribution of SLCP to California emissions and applicability of GWP* to emissions inventories

Mitigating SLCP emissions from dairy production centers on reducing CH_4 emissions from dairy manure management and reducing CH_4 from enteric fermentation. California has the largest dairy herd in the United States and thus the highest total (enteric fermentation plus manure management) dairy CH_4 emissions. California milk production feed efficiency is relatively high, making enteric fermentation emissions per unit California milk product relatively low (Naranjo et al., 2020). However, CH_4 emissions from cows in California are relatively higher on a per-dairy basis than those in the rest of the United States herd because flush water lagoon systems are the predominate manure management system in California dairies (CARB, 2022b), and anaerobic lagoons emit the most CH_4 per head of all common manure management practices (Owen and Silver, 2015). In 2017, agricultural manure management was California's second largest source of CH_4. Thus, preventing anaerobic conditions during manure management or capturing transforming CH_4 that is produced in anaerobic conditions represent major opportunities to reduce CH_4 from manure management (Montes et al., 2013). The CDFA Dairy Digester Research and Development Program (DDRDP) provides grants to finance the installation of dairy digesters, which capture CH_4 and convert it into fuel (CDFA, 2022b). CDFA's Alternative Manure Management Program (AMMP) provides grants to finance implementation of non-digester manure management practices in order to manage less manure anaerobically, such as solid separation or conversion from flushing to scraping or pasture-based management (CDFA, 2022a). Thus, CDFA's manure management CH_4 emissions reductions programs encompass both major targets for reductions. We have shown in this study that CDFA's programs, especially DDRDP, have successfully mitigated CH_4 emissions and have contributed to the decreasing CH_4 emissions rate in California since 2008.

In 2017, enteric fermentation was California's largest source of methane. Mitigation strategies for enteric fermentation center on use of feed additives such as rumen archaea inhibitors, ionophore antibiotics, or electron acceptors like nitrates (Hristov et al., 2014), and improved feed digestibility, which is unlikely to yield significant benefits in intensive production systems like California that already have relatively high feed efficiency (Herrero et al., 2016). 3NOP inhibits the methane-forming step in the rumen and is a promising feed additive, but production of 3NOP also emits GHG, decreasing net potential reductions (Feng and Kebreab, 2020). In this study, we evaluated reductions scenarios that included enteric fermentation CH_4 reduction, using maximum net potential 3NOP reductions. For our manure management reduction scenarios, we used 40% reduction of 2013 levels as mandated by SB 1383 without evaluating the feasibility of these reductions and assumed 40% represented net reductions. For this reason, enteric fermentation's relatively smaller impact on emissions reductions in our scenarios is not necessarily representative of its true impact relative to manure management mitigation programs. Indeed, over the past 50 years in California, reductions in CH_4 from enteric fermentation have been about five times greater than reductions in CH_4 from manure management (Naranjo et al., 2020). However, because California SB 1383 does not require any specific enteric fermentation reductions, we used potential net 3NOP reductions, while we assumed that 40% manure management methane reductions were feasible because they are mandated by SB 1383. Nonetheless, our study demonstrated that GWP* can accurately represent the warming effects of CO_2eq under potential enteric fermentation CH_4 reductions and thus can serve as an important tool of evaluating on-farm CH_4 mitigation strategies in the future.

We used 2017 enteric fermentation emission factors to calculate emissions from dairy cows from 2017 to 2029 under the "business-as-usual" scenario, assuming that enteric fermentation emissions factors would be stable from 2017 to 2029. However, the true dynamics of future enteric fermentation emissions factors may be more complex. Enteric CH_4 emissions factors for California dairy cattle remained constant from 2012 to 2020 (CARB, 2022a). In contrast, U.S.-wide emissions factors increased by 8.7% from 2010 to 2020 (EPA, 2022). The relative stability of California dairy enteric CH_4 emissions factors may reflect interplay between increasing milk production and improvements in feed efficiency. Increased per capita milk production could associated with greater feed intake and thus increasing enteric CH_4 emissions factors, as both CARB and EPA develop enteric CH_4 emissions factors CH_4 conversion rate, which is the fraction of gross energy (GE) in feed converted to CH_4, and GE intake increases with increasing net energy for lactation (NE_L), which itself increases with increasing milk production (IPCC, 2006; CARB, 2022a; EPA, 2022). However, a life cycle analysis comparing California dairy environmental footprints in 1964 and 2014 found that in 1964, the feed conversion rate was 1.93 kg feed per kg energy-corrected milk (ECM), while in 2014, the feed conversion ratio was 0.79–0.81 kg of feed/kg of ECM, suggesting cattle today utilize feed more efficiently than those 50 years ago. In 1964, each cow emitted 0.98 kg of CO_2 equivalents of enteric methane per kg ECM compared with 0.43–0.45 kg of CO_2 equivalents of enteric methane per kg ECM in 2014 (Naranjo et al., 2020). Average ECM production in 1964 was 15.73 kg/day, while it was 39.8 kg/day in 2014, making enteric methane emissions factors 15.4 kg CO_2 equivalents per day in 1964 and 17.11–17.9 kg CO_2 equivalents per day in 2014.

Previous authors have predicted future inventories of livestock methane emissions assuming constant or even decreasing CH_4 emissions intensities (emissions per unit product, where product is kg of protein in this case) (Chang et al., 2021). Chang et al. projected livestock methane emissions out to 2050 using different pathways of assumed emission intensity changes. These authors used two pathways with contrasting assumptions about production efficiency changes: constant emission intensity and improving efficiency (i.e., decreasing emission intensity). The "constant intensity" pathway assumed that no changes in methane emission intensities would take place in the future. The "improving efficiency" pathway was based on decreasing trends in emission intensity during the past two decades due to increasing production efficiency. Based on this finding, they constructed a "improving efficiency" pathway, assuming continuing decreases in emission intensity. Under this pathway, emissions intensities in countries showing decreasing emission intensity during the past two decades followed this decreasing trend into the future, while a constant emission intensity was applied for countries that experienced no change or an increasing emission intensity in the past two decades. Thus, other studies in the field have found it reasonable to assume constant emissions intensity of livestock products into the future. The assumption that increasing production efficiency will lead to constant or decreasing emissions intensities is not necessarily the same as the assumption that increasing production efficiency will lead to constant emissions *factors*, because increasing production could still lead to increasing total (e.g., not on a per-product basis) emissions. However, enteric CH_4 emissions factors for California dairy cattle given by CARB remained constant from 2012 to 2020. Over this time, California milk production was as follows: 23,457 lbs. per head in 2012; 23,178 lbs. per head in 2013; 23,786 lbs. per head in 2014; 23,028 in 2015; 22,968 in 2016; 22,755 in 2017; 23,301 in 2018; 23,533 in 2019; and 23,990 in 2020 (USDA National Agricultural Statistics Service, 2022). Annual change in milk production, averaged over these 8 years, is 0.26%. Thus, if milk production was approximately constant, and milk emissions intensity was approximately constant or decreasing, then enteric CH_4 per cow (e.g., enteric CH_4 emissions factor) could remain approximately constant.

Because CH_4 emissions factors are estimated based on dietary and production parameters, if regionally typical diets and production remain approximately the same over time, emissions factors will remain the same from year to year. CARB likely has assumed that the diets of California dairy cattle have remained approximately constant, given that the emissions factors they have calculated remain constant from 2012 to 2020. Thus, several lines of evidence underscore that it is a reasonable assumption that enteric fermentation factors will remain approximately constant to 2029 in the BAU scenario. However, this trend does not necessarily apply to other states and production situations, and enteric fermentation emissions factors may be more variable than assumed in our study. In the BAU scenario, this assumption led to approximately constant annual CH_4 emissions, and thus declining GWP* emissions over time. Had enteric CH_4 emissions factors continued to rise over time, the dynamics of the scenario would be similar to the historic (1950–2017) scenario, in which enteric CH_4 emissions factors and annual CH_4 emissions did increase over time. The purpose of our "BAU" scenario was to investigate GWP* dynamics relative to GWP dynamics given approximately constant annual CH_4 emissions. The "BAU" scenario utilized projected dairy cattle population data to estimate future populations under typical policy and macroeconomic conditions and projected a 0.32% decrease in population from 2018 to 2029. This small decrease in population over time, along with the constant enteric fermentation and manure management CH_4 emissions factors used, gives approximately constant annual CH_4 emissions and provides a scenario to investigate the difference in dynamics between GWP- and GWP*-based estimates under *constant* background CH_4 emissions, unlike the historical (increasing background emissions) or reductions (decreasing background emissions) scenarios. Thus, while further investigation on trends in enteric fermentation and manure management emissions factors and future dairy cattle populations is needed, the assumption of constant California CH_4 emissions factors from 2017 to 2029 is in line with CARB emissions factors and sufficient for our study's purposes.

The goal of California's annual GHG emission inventory is to establish historical emission trends and track sectoral progress in achieving statewide reductions goals. The 2021 edition of the inventory and previous iterations provide emissions estimates in CO_2eq using GWP_{100} values from IPCC AR4, consistent with current international and national GHG inventory practices (CARB, 2022a). In addition, SB 1383 mandates reductions in annual emissions rates, not warming effects, of dairy manure CH_4 by 2030. Thus, because goals are centered on emissions reductions, not warming impacts, GWP may still be an appropriate metric for these purposes. However, attribution of the warming impacts of the economic sectors whose emissions are quantified in emissions inventories requires a metric that can capture the dynamics of cumulative SLCP emissions over time, such as GWP*. GWP* and GWP could coexist given the different policy goals of economic sectors or state or local governments, as recommended by the IPCC AR6 Working Party I report.

4.5. Limitations of GWP*

Notwithstanding GWP*'s improved representation of CH_4's flow gas-nature, any single-number metric may result in oversimplification of complex climate dynamics and underestimation of the warming response to SLCP emissions (Collins et al., 2020). Some arbitrary decisions still underlie GWP*, such as the time horizon H, or the designation of a certain climate pollutant as "short-lived" and thus the employment of GWP*, which depends on the time scale being considered (Lynch et al., 2020). While the calculation of GWP* is subject to some arbitrary decisions, the concept of CO_2eq is not necessarily physically accurate. Climate responses to CO_2 and CH_4 are both temperature- and scenario-dependent, so different emissions scenarios with identical CO_2eq can have vastly different impacts on global temperature. For this reason, no single scaling factor can truly convert between CO_2 and CH_4 emissions across all scenarios (Fuglestvedt et al., 2000).

Previous authors have suggested that because it is based on past emissions, GWP* unfairly and unethically penalizes developing countries when applied at sub-global levels (Rogelj and Schleussner, 2019). Rogelj and Schleussner argue that due to GWP*'s "grandfathering" effect, countries with high historic SLCP emissions are rewarded because reductions from these emissions lead to declining cumulative CO_2we, while countries with historically low SLCP emissions (i.e., typically developing countries) are penalized for increasing emissions which may result from socioeconomic development. While not stated in this critique, presumably similar limitations apply to emissions from specific economic sectors. In their response, Cain et al. (2021) note that this "unintentional unfairness" would result from any warming-equivalent-based metric that differentiates the behavior of stock and flow pollutants, such as combined global temperature change potential (CGTP) (Collins et al., 2020). Furthermore, because IPCC AR6 does not recommend any given emission metric, metric appropriateness depends on given policy goals. Cain et al. (2021) argue that in policy contexts with long-term temperature goals as the Paris Agreement, GWP* is useful because it demonstrates that the relationship between a country's CH_4 emissions and temperature change scales with current CH_4 emissions plus a contribution from past CH_4 emissions, which conventional GWP cannot. They argue that quantifying this relationship is not itself necessarily unfair or unequitable, given that quantification of historical contributions of a country's SLCP to warming using GWP* and taking these contributions into burden-sharing policy are separate, and the latter are determined by policy-makers, although using a metric that reflects the impact of all gases on temperature change would facilitate such policy discussions (Cain et al., 2021).

In spite of potential limitations of the CO_2 equivalence concept and GWP*, CO_2-equivalence-based climate metrics remain a prevalent policy tool (UNFCCC, 2020). GWP* provides an accessible and temperature goal-relevant adjustment of current CO_2-equivalence methodology that does not require any additional information from what is already typically reported. Other metrics that have been proposed as alternatives to GWP, such as Global Temperature Change Potential (GTP), combined GWP, or CGTP, require additional inputs that are themselves dependent on uncertainties in the climate system and future emissions scenarios (Shine et al., 2007; Collins et al., 2020). GWP* has been shown to underestimate the contribution of CH_4 to temperature change by up to 20% compared to CGTP, which employs a more explicit calculation of the effect of CH_4 emissions rate change relative to a pulse emission of CO_2 (Collins et al., 2020). However, Collins et al. (2020) also note that the more complex emissions metrics CGWP or GTP are structurally similar to GWP* and provide only changes in precise values, not conceptual foundation or development, whereas using the conventional GWP is unable to represent the correct sign of warming from decreasing SLCP emissions, as we have shown. While Wigley (1998) argues that unlike the GWP framework, emissions equivalence should be based on radiative-forcing based Forcing Equivalence Index (FEI), other authors consider both GWP and GWP* reasonable approximations to FEI (Enting and Clisby, 2021).

5. Conclusions

We have used California dairy production as a case study for the application of the novel GHG metric GWP*, following its recent development and publication. While recent publications have shown the applicability of GWP* to global emissions datasets spanning all SLCP emissions sectors, we have applied GWP* to a California dairy CH_4 emissions inventory and discussed the applicability of GWP* to local and single-sector inventories, which some authors argue is limited. GWP* provides a direct relationship between cumulative emissions and their warming effects, which conventional GWP does not. This relationship exists because GWP* represents methane's short-lived nature, by which it does not accumulate in the atmosphere under declining emissions, unlike CO_2. We found that conventional GWP underrepresents the warming impacts of dairy CH_4 emissions in CA under increasing emissions rates, and overrepresents their warming impacts under declining emissions rates. GWP* represents that under declining emissions rates, cumulative California dairy CH_4 decrease and warming forced by these emissions also decreases, although any CH_4 that continues to be emitted is still a strong climate forcer. In contrast, under declining annual CH_4 emissions, GWP-based CO_2-equivalent emissions (CO_2eq) continued to accumulate, so GWP did not indicate the correct direction of temperature change. While IPCC AR6 makes clear that metric choice depends on policy goals, given its ability to unambiguously link warming impacts to SLCP emissions, GWP* may provide a more accurate tool for quantifying SLCP emissions into policy contexts that specifically aim to limit global warming, such as the Paris Agreement.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EP designed the research approach, compiled data, wrote the R code to analyze the results, analyzed the results, and prepared the manuscript. SL helped design the research approach and provided data and support in carrying out the research. FM proposed the research question and supervised the work. All authors reviewed drafts of the manuscript, provided feedback, and approved the final version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.1072805/full#supplementary-material

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