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REVIEW

The path to climate neutrality for California dairies

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Abstract

In recent years, dairy farms have come under scrutiny with pressure to curb their environmental impacts. Since 1950, the California dairy industry has made strides in reducing greenhouse gas (GHG) emissions per kilogram of milk produced. However, total GHG emissions have remained near constant over the past 15 years. Most on-farm dairy production emissions are in the form of methane (CH_4) emissions produced via enteric fermentation, where CH_4 is produced as a byproduct of feed digestion, and manure management. Methane is a powerful but short-lived GHG. Historically, GWP100 has been utilized to describe a GHG emission's warming impact over a 100-year time span. To better characterize the impact of CH_4 on atmospheric warming, a relatively new accounting system named global warming potential star (GWP*) has been proposed to consider the production and degradation of this short-living GHG. Characterizing greenhouse gases by how they warm our atmosphere instead of the number of emissions produced is a better metric for the true impact of the emissions on atmospheric warming.

The goal of this research is to use GWP* to analyze the impact of potential GHG emissions scenarios from California dairy and the impact of those scenarios on atmospheric warming. Utilizing GWP* can help discern when an industry or sector has achieved climate neutrality or no annual warming contributions from industry. This paper also investigates the necessary amount of CH_4 reduction needed and the time point at which the dairy sector can achieve climate neutrality. The scenarios are business-as-usual (BAU), 40% reduction in manure CH_4 emissions (40 MAN) by applying anaerobic digestion and its alternative technologies, and 40 MAN along with a 10.6% reduction in enteric fermentation CH_4 emissions via 1/3 of California's cows fed the feed additive 3-nitrooxypropanol (40 MAN+EF). Under GWP100 in 2030, carbon dioxide equivalents (CO_2e) for the 40 MAN and the 40 MAN + EF scenarios were reduced by 18 and 22%, respectively compared to the BAU. For all three scenarios, the relative warming impact of the industry decreased over time due to constant herd sizes and total annual emissions. By aggressively decreasing CH_4 emissions under the 40 MAN and 40 MAN+EF scenarios, there is the possibility for the California dairy industry to reach climate neutrality by the year 2027. These scenarios have more CH_4 naturally removed in the atmosphere than is emitted, thus lowering atmospheric contributions from the industry. These scenarios could be adopted by dairies in other states and countries to help the global dairy industry to achieve climate goals through persistent CH_4 mitigation.

Keywords: GWP*, methane, atmospheric warming, sustainable agriculture

Introduction

The California dairy industry is the state's leading commodity, producing over 19 billion kilograms of milk per year which generates over $7.4 billion of the nearly $50 billion California agriculture industry (CDFA, 2021). Dairy farms also make up 45% of California's annual methane (CH_4) budget with 25% resulting from manure management and 20% from enteric fermentation (California Air Resources Board (CARB), 2022b). This potent greenhouse gas (GHG) has come under scrutiny in recent years with the passage of legislation and pressure to reduce the environmental impact of milk production. In March 2017, the California Air Resources Board (CARB) approved the Short-Lived Climate Pollutant (SLCP) Reduction Strategy to reduce CH_4 emissions based on Senate Bill 1383 (State of California, 2016). This mandates the entire dairy industry to reduce the 2013 manure management CH_4 emissions by 40% by 2030. The California legislature does not currently mandate enteric fermentation CH_4 reductions. However, regulations are likely to be created in the future to meet California's climate goals (State of California, 2006).

SLCPs are a category of pollutants that have lifetimes much shorter than CO_2 from days to a few decades. Along with CH4, other pollutants in this category include black carbon tropospheric ozone, and CH_4, which have lifetimes of days, weeks, and 12 years, respectively (Haines *et al*., 2017). Once CH_4 is produced and released to the atmosphere, the majority will be oxidized to CO_2 via the process of hydroxyl oxidation in about 12 years

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(Cantrell *et al*., 1990; Kirschke *et al*., 2013). The produced CO_2 can then remain in the atmosphere for up to 1000 years or be taken up by various carbon dioxide sinks (Solomon *et al*., 2009; Muñoz and Schmidt, 2016). Although this CO_2 is long living in the atmosphere, these emissions are part of the biogenic carbon cycle whereby the carbon is taken up by the feedstocks that are utilized as a source of dairy feed (Muñoz and Schmidt, 2016). As a result, no new carbon is added to the atmosphere, but simply recycled. Reducing SLCPs has been proposed as a major opportunity to slow projected global warming by 0.5°C over the next 25 years (Shindell *et al*., 2017).

Conventionally, the 100-year global warming potential (GWP100) metric has been used to determine the 100-year time-integrated climate impact of a GHG. A GHG's GWP100 calculation is determined by comparing the emissions of a one-ton pulse of the GHG of interest over a 100-year period compared to a one-ton pulse emission of CO_2 (Reay *et al*., 2007). The application of the conventional GWP100, for converting SLCPs into CO_2 equivalents, often misrepresents the impacts of the SLCPs on global temperature (Allen *et al*., 2016). Therefore, GWP* was proposed to relate the rate of SLCP emissions to CO_2 emissions and their subsequent impact on warming (Allen *et al*., 2018).

GWP* can be used to determine the effects of mitigation efforts on future annual emissions and warming impacts (Smith *et al*., 2021). Under GWP100, CH_4 emissions in a scenario in which emissions are increasing, are undervalued as more CH_4 is produced than removed from the atmosphere, whereas, in a constant or falling scenario, CH_4 emissions are consistently overvalued as an equal or greater amount is removed than produced respectively (Allen *et al*., 2018). GWP* can predict the cooling effects that result from reductions in SLCP emission rates (Cain *et al*., 2019). Climate neutrality is achieving no additional warming impacts from the activities of a firm or an entity at regional, subnational, and national scales (Pineda and Faria, 2019). While net zero GHG emissions are achieving the balance between the metric-weighted anthropogenic GHG emissions from an entity with the metric-weighted anthropogenic GHG removal over a specific period (Pineda and Faria, 2019; Matthews *et al*., 2021). Thereby under net zero emissions, everything produced in a given year must be taken out of the atmosphere or offset, whereas climate neutrality focuses on the annual warming contribution for those gasses produced and removed in a given year.

Applying GWP* to predict the warming impact of the U.S. dairy industry's CH_4 emissions on climate showed that the CH_4 emissions alone, not accounting for other greenhouse gasses of production, have not contributed to additional warming from 1986 to 2017 (Liu *et al*., 2021). Furthermore, the industry will approach climate neutrality by 2031 for CH_4 emissions alone if they are reduced by 1% per year (Liu *et al*., 2021).

Dairy anaerobic digesters and other manure management technologies, and feed additives have been employed across dairy farms to reduce CH_4 emissions from manure and enteric fermentation, respectively (Rotz, 2018). The California Department of Food and Agriculture (CDFA) has established the Dairy Digester Research and Development Program (DDRDP) and the Alternative Manure Management Practice (AMMP) program to help dairy farms install anaerobic digesters and other manure management technologies to reduce CH_4 emissions. Research has demonstrated 3-nitrooxypropanol (3-NOP) to be an effective CH_4 reducer; however, its application is still limited on farms without regulatory approval (Melgar *et al*., 2020).

To understand the impact that California dairy can have on future atmospheric warming, there is a need to determine the effect of emission reductions resulted from the increase of manure management technologies and feed additives. Therefore, the objectives of this study were to determine: (1) the atmospheric warming impact of the California dairy industry; and (2) the time frame by which the California dairy industry could achieve climate neutrality via the use of anaerobic digestion and alternative manure management and feed additive technologies from 2019 to 2030.

Review methodology

The present review comprises GHG emission data and associated literature for the California dairy industry and its respective impact on atmospheric warming. Data was obtained from the California Air Resources Board (CARB) and the United States Department of Agriculture (USDA) National Agriculture Statistics Service (NASS) to assess emissions and cattle population, respectively. Relevant literature was obtained from searching databases for scientific manuscripts relevant to dairy's impact on climate. Discussions were conducted with experts to determine relevant material for this review.

Materials and methods

CALIFORNIA DAIRY INDUSTRY DATA COLLECTION

California dairy cattle production and California dairy GHG emissions data were collected from the United States Department of Agriculture (USDA) and California Air Resources Board (CARB), respectively (Naranjo *et al*., 2020; California Air Resources Board (CARB), 2022b). Dairy cattle production data included lactating cow and heifer populations as of January 1st of each year and annual milk production from 1990 to 2020. Emissions data from CARB were collected from the state's scoping plan over the years 2000–2019 (California Air Resources Board, 2021). The data included enteric fermentation CH_4, manure management CH_4, and manure management nitrous oxide (N_2O). The available data from 2000 to 2019 was used to predict the enteric fermentation and manure management emissions of CH_4 and N_2O for the years 1990–1999. Multiple linear regression models were employed, using R Software (version 4.1.3), to predict the emissions of CH_4 and N_2O as a function of both annual milk yield per cow and lactating herd number as follows:

Enteric CH_4 (Million metric tons; [MMT]) $= -0.23 + 1.45 \times 10^{-7} X_1 + 2.75 \times 10^{-5} X_2$ $R^2 = 0.87$

Manure Management CH_4 (MMT) $= -0.504 + 2.34 \times 10^{-7} X_1 + 4.63 \times 10^{-5} X_2$ $R^2 = 0.89$

Manure Management N_2O (MMT) $= -4.11 \times 10^{-4} + 7.51 \times 10^{-10} X_1 + 4.26 \times 10^{-8} X_2$ $R^2 = 0.77$

Where:

X_1 = Lactating cow population;

X_2 = Annual milk yield, kg/cow.

Indirect emissions from dairy farm operations (feed production, energy use, etc.) were assumed at 0.24 kg carbon dioxide equivalents (CO_2e)/kg milk (Naranjo *et al*., 2020).

GWP VS. GWP* ACCOUNTING CALCULATIONS

The emission data of CH_4 and N_2O were converted to CO_2e to calculate the industry's GWP100 under AR5 scoping values (IPCC, 2014):

$$\text{GWP100 } (CO_2e) = CO_2 + 28 \times CH_4 + 265 \times N_2O \quad (1)$$

To transition from the production of the industry's emissions to the warming impact, GWP* was utilized from 2010 onward due to the 20-year timespan needed for metric calculations (Smith *et al*., 2021). Equation 2 was developed based on the concepts developed by Smith *et al*. (2021) to convert GWP100 to GWP*:

$$\text{GWP* } (CO_2we) = CO_2 + 4.53\, CH_4(t) - 4.25\, CH_4(t-20) + 265 \times N_2O \quad (2)$$

Where t is equal to the current year being analyzed.

SCENARIOS TO REDUCE ATMOSPHERIC WARMING IMPACT OF THE CALIFORNIA DAIRY INDUSTRY

Three scenarios were proposed and analyzed to determine the industry's projected warming between the present year (2019) and the target year (2030). The three scenarios included (1) a business-as-usual (BAU) where all industry emissions were assumed to stay constant; (2) a 40% reduction in manure management CH_4 emissions (40 MAN) in line with SB 1383; and (3) the 40 MAN emissions along with an assumed 10.6% reduction in total enteric fermentation CH_4 emissions (40 MAN+EF). The 40 MAN reduction was assumed to be met via the construction of anaerobic digesters and alternative manure management techniques such as manure solid separators and weeping walls. The 10.6% reduction in the total enteric fermentation CH_4 emissions was estimated by assuming one-third of the California dairy industry's cows would be receiving 3-NOP, which has an estimated 31.7% reduction in CH_4 emissions when fed at a rate of 127 mg/kg of dry matter (Feng and Kebreab, 2020). For the industry's CH_4 emission scenario projections, consistent emissions reductions were assumed to meet the stated goals between the present year (2019) and the goal year (2030). The year 2019 is assumed to be the present year because that is the year with the most recently available scoping plan (California Air Resources Board (CARB), 2022b).

Additionally, milk production was assumed to continue the similar trend observed from 1990 to 2020 with a 0.8% increase in annual milk produced per cow through 2030 (Fig. 1). The proposed milk yield increase of 0.8% annually is a reasonable assumption that is justified by another study that projected USA milk yield will continue to increase within the next 50 years (Britt *et al.*, 2018). They mentioned that the milk yield will climb at an accelerated rate and will be doubled by 2067 based on current production levels due to genetic selection that will positively affect yield and health traits, and improvements in feed quality and management. Although cows are sensitive to changes in temperature, as will be increasingly likely in the future, additional management in cooling cows and genetic merit gains will help offset the increasingly warmer environment (Gunn *et al.*, 2019).

Lactating cow numbers were expected to reduce by 0.5% annually in line with CARB's scoping goals and suggestions on how SB 1383 will be achieved (California Air Resources Board (CARB), 2022b). The California lactating herd reached its absolute maximum in 2009 and has begun to slightly decrease in recent years due to the migration of dairy cows to other states and resource challenges within California (Fig. 1). Along with this, manure management N_2O emissions were assumed to be held consistent from current emissions levels between 2019 and 2030.

Under all three evaluated scenarios, GWP100 and GWP* were calculated to determine the associated GHG emissions and the warming impact of the respective emissions. The California dairy industry was determined to achieve climate neutrality when the warming impact of the industry reached zero or went below zero annual carbon dioxide warming equivalents (CO_2we).

Results

HISTORIC DAIRY POPULATION AND GHG EMISSIONS

Methane emissions represent approximately 75–80% of the California dairy industry's GHG emissions from farm to gate, based on GWP100 (Fig. 2). With a similar number of lactating cows since 2007, the industry has stayed stable at 24–25 million metric tons of CO_2e annually. The California herd achieved its absolute maximum lactating-cow population in 2009 with 1.84 million animals (Fig. 1) and has maintained consistent levels with a lactating herd population of 1.75 million lactating cows from approximately 2007–2019 (USDA, 2022). In recent years, the lactating herd population decreased to 1.72 million cows due to cows migrating to other states and resource challenges present in California.

SCENARIO GHG EMISSIONS

Beginning with the BAU scenario, the industry continues its historic environmental gains by producing more milk (18.41 vs. 19.43 billion kilograms) with a fewer number of cows in 2019 compared to 2030 (1.73 vs. 1.64 million) as shown in Table 1. This results in a decrease in GHG emission intensities or GHG emissions per kg of milk (1.37 vs. 1.29 kg CO_2e per kg of milk). However, there is no pronounced difference in the total GHG emissions contributed by the industry (24.41 vs. 24.65 MMT CO_2e) due to gains in milk

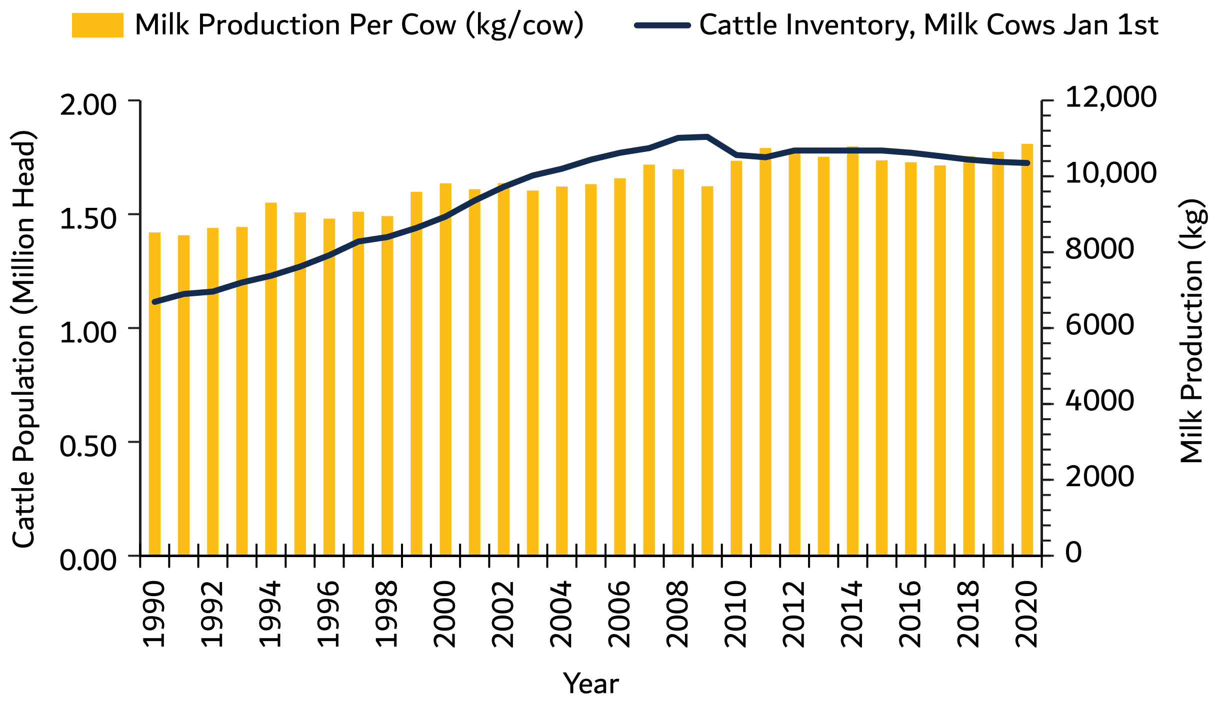

Fig. 1. California dairy industry lactating cow population and milk yield per cow from 1990 to 2020 (Naranjo *et al.*, 2020). Lactating cattle population is referenced from the United States Department of Agriculture National Agricultural Statistics Service based on estimates of animal numbers based on January 1st of each year.

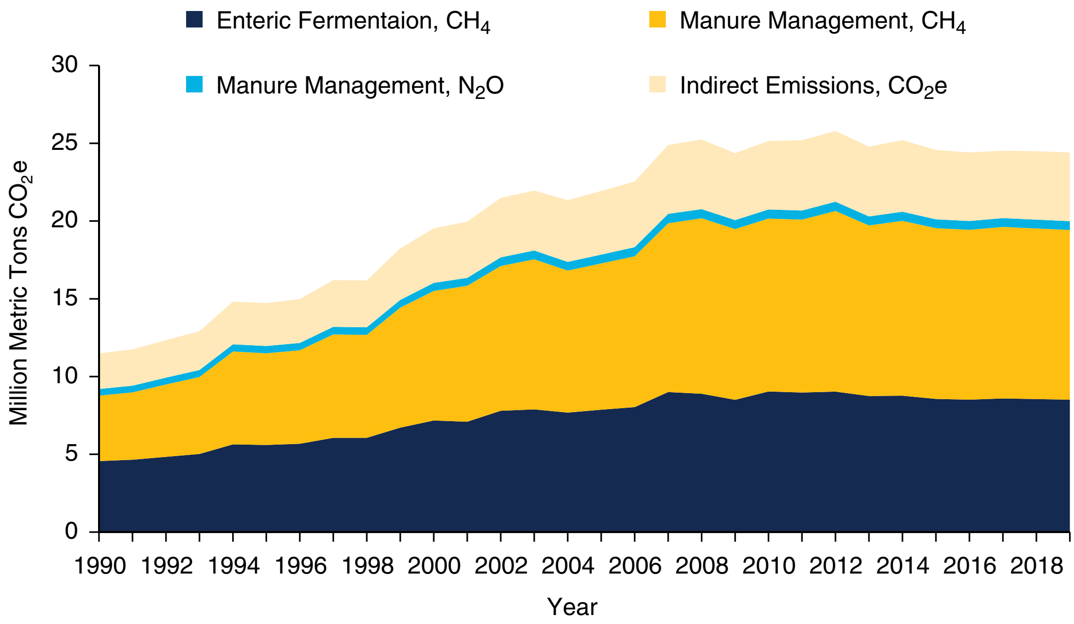

Fig. 2. California dairy industry's greenhouse gas emissions profile by dairy farm source from 2000 to 2019 (California Air Resources Board (CARB), 2022a). Indirect emissions include everything that is necessary for dairy production including emissions associated with feed production and farm management. Data here is reported in carbon dioxide equivalents and includes carbon dioxide and nitrous oxide emissions (IPCC, 2014).

Table 1. California cow population, production parameters, and greenhouse gas emissions under Business-as-Usual scenario between 2019 and 2030.

	2019	2025	2030
Number of Lactating Cows (Million)	1.73	1.69	1.64
Milk Production Per Cow (thousand kgs/year)	10.64	11.33	11.82
Total Milk Production (Billion kg/year)	18.41	19.09	19.43
Enteric Emissions (MMT CO_2e)	8.51	8.51	8.51
Manure CH_4 Emissions (MMT CO_2e)	10.91	10.91	10.91
Total CO_2e Emission (MMT[1])	24.41	24.57	24.65
Cradle to Farmgate Footprint (kg CO_2e/kg milk[2])	1.37	1.32	1.29
CO_2we Emissions (MMT[3])	31.65	19.69	7.54
Cradle to Farmgate Warming Footprint (kg CO_2we/kg milk)	1.72	1.03	0.39

[1]CO_2e emission calculated based on using global warming potential 100 (GWP 100) factors from AR 5 of 1 for CO_2, 28 for CH_4, and 265 for N_2O (Smith *et al.*, 2021).
[2]Includes all emissions divided by the number of milk production (kg) per year.
[3]Calculated using GWP* (Cain *et al.*, 2019).

production per cow without a change in overall emissions. From 2019 to 2030, the 40 MAN scenario reduces industry manure management CH_4 emissions from 0.37 to 0.24 MMT CH_4 and the 40 MAN+EF scenario reduces enteric fermentation CH_4 from 0.30 to 0.27 MMT CH_4 through implementing 3-NOP. By implementing the 40 MAN and 40 MAN+EF scenarios, the industry's total GHG emissions decreases by 2030 from 24.41 to 20.15 and 19.16 MMT CO_2e, respectively (Fig. 3).

Regardless of the scenario studied, based on the GWP* approach, the warming impact of the GHG profile decreases over time due to consistent herd populations and emission factors (Fig. 4). However, even though CH_4 emissions are consistent under the BAU scenario, outstanding emissions from indirect and N_2O sources prevent climate neutrality from being achieved. By aggressively decreasing CH_4 emissions under the 40 MAN and 40 MAN+EF scenarios, there is the possibility for the California dairy industry to reach climate neutrality by the year 2027. By this target year, the industry has the potential to reach climate-negative milk production, whereby warming equivalents are going below zero and the industry is offsetting historical emissions contributions.

ATMOSPHERIC WARMING IMPLICATIONS FOR THE PROPOSED SCENARIOS

Analyzing the cumulative warming emissions of the scenarios from 2019 to 2030 creates a divergence in the impact on atmospheric warming between scenarios. By using the assumption that one Tera ton of CO_2 we raise the global atmospheric temperature by 1.8°C (Smith *et al.*, 2021), then under BAU the atmosphere would see an

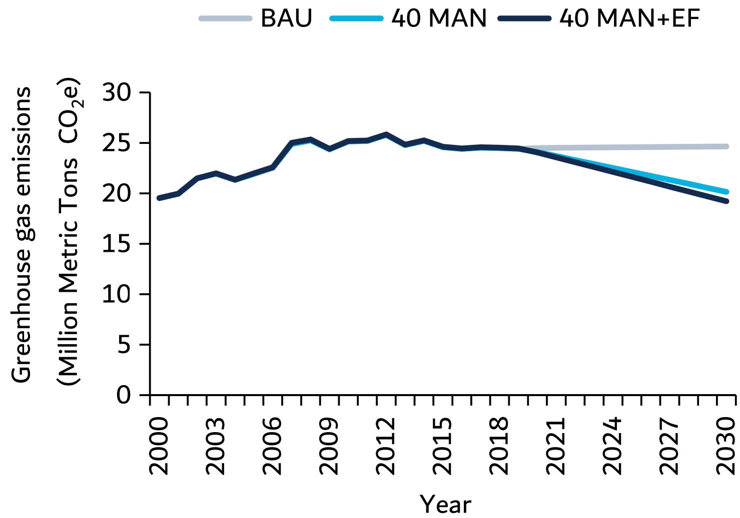

Fig. 3. California dairy industry's annual greenhouse gas emissions between the various scenarios analyzed from 2000 to 2030. Business as Usual (BAU) assumes a continuation of California dairy industry trends of a slight decrease in herd population. 40 Manure (40 MAN) assumes a 40% reduction in manure management emissions scenarios in line with SB 1383 legislation. 40 Manure + enteric fermentation (40 MAN+EF) assumes a reduction in manure management emissions as well as a 10.6% decrease in enteric fermentation emissions.

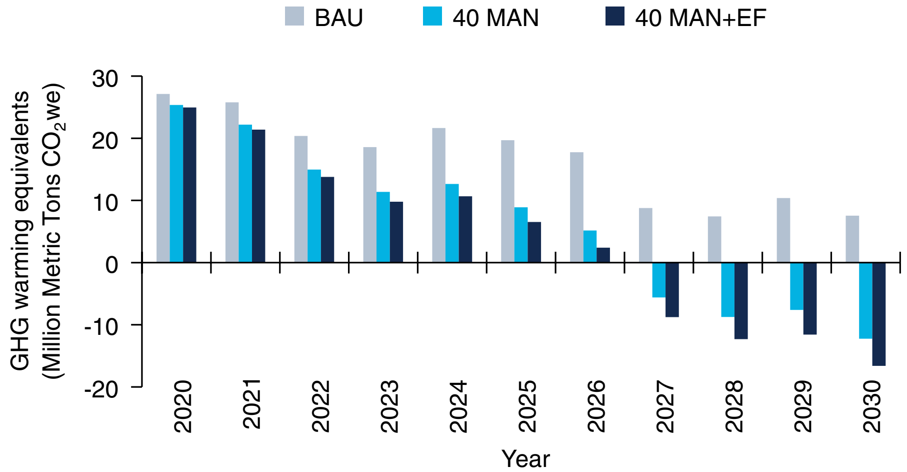

Fig. 4. California dairy industry annual warming impact of greenhouse gas emissions based on the three analyzed scenarios from 2020 to 2030. Business as Usual (BAU) assumes a continuation of California dairy industry trends of a slight decrease in herd population. 40 Manure (40 MAN) assumes a 40% reduction in manure management emissions scenarios in line with SB 1383 legislation. 40 Manure + enteric fermentation (40 MAN+EF) assumes the reduction in manure management emissions as well as a 10.6% decrease in enteric fermentation emissions.

increase by 3.33×10^{-4} °C through the remainder of the decade (Cain *et al.*, 2019). Likewise, the 40 MAN and 40 MAN+EF scenarios would result in an increase in warming of 1.21×10^{-4} and 7.71×10^{-5} °C, respectively. Although climate neutrality can be achieved under these scenarios, this metric is only achieved on an annual basis starting in 2027. The industry will still contribute positive GHG emissions and warming from 2019 until climate neutrality is realized, which causes the projected warming to occur when measuring over the entire scenario timeline. Once climate neutrality has been accomplished, the CH_4 reductions are not great enough to overcome historical industry emissions in the form of CO_2 and N_2O throughout the scenario period. Additional reductions in CH_4 emissions are necessary to continue to decrease the warming impact of the industry in the decades to come (Smith *et al.*, 2021). Further modeling techniques utilizing either the FaIR model or other climate modeling software are needed to understand the sensitivity of these changes in emission metrics to their impact on global atmospheric temperatures (Allen *et al.*, 2018).

Discussion

The studied scenarios are the first to look at how policy and implementation of CH_4 reduction strategies will reduce California dairy's atmospheric warming contributions. By implementing manure management strategies via the creation of manure anaerobic digesters and feed additives, the industry can achieve climate neutrality as early as 2027. The industry's warming impact will decrease over time, with constant herd populations and aggressive reductions in CH_4 by applying manure management technologies and enteric fermentation inhibitors. Not to mention that CH_4 is a precursor for forming ozone molecules, which have detrimental impacts on both human health and crop performance (Van Dingenen *et al.*, 2018). Thereby aggressive on-farm reductions of CH_4 can have multiple benefits for agriculture production, ecosystems, and the planet.

CALIFORNIA DAIRY'S PROGRESS TOWARD CLIMATE GOALS

Since the implementation of SB 1383, the California Department of Food and Agriculture (CDFA) has provided grants in combination with private investment to help to construct or begin construction of approximately 113 projects throughout the state (CDFA, 2022b). The biogas produced from these digesters has been used for electricity generation, fuel cells, or upgraded into renewable natural gas. Additionally, CDFA's Alternative Manure Management Program (AMMP) grants have constructed 114 projects, which include mechanical lagoon solid separators, compost-bedded pack barns, and weeping walls (CDFA, 2022a). These technologies help to separate the organic matter, which would traditionally undergo anaerobic biochemical processes during manure storage and produce CH_4 and other GHGs (Montes *et al*., 2013).

To meet the State's climate goals, one of the pathways the dairy industry can pursue is to continue employing manure management technologies and feed additives to reduce manure and enteric fermentation CH_4, respectively. One of the limitations to our scenario is that 3-NOP is not currently available for sale in the U.S., but it is expected to achieve regulatory approval within the next few years given its prior approval in Brazil, Chile, and the European Union (Feng and Kebreab, 2020; Mitloehner *et al*., 2020). It is currently going through regulatory approval as a veterinary drug in the United States, with anticipation that it could be first approved in 2024 (Mitloehner *et al*., 2020). Over the next few decades, there will likely be other feed additive candidates that can be utilized to reduce enteric CH_4. Another candidate to reduce enteric CH_4 is red seaweed (*A. taxiformis*), but further work such as sourcing large enough quantities and ensuring palatability is needed before it is widely adopted across farms (Vijn *et al*., 2020; Stefenoni *et al*., 2021). Furthermore, dairy digesters will continue to be a crucial tool to reduce manure CH_4 emissions. California currently has 236 dairy digesters, which collect and harvest CH_4 from 254 dairy farms throughout the state (Dairy Cares, 2022). However, with CDFA-funded dairy digester projects through 2023, the industry will be 42.6% of the way toward the SB 1383 goal (CDFA, 2022b). To meet the remaining GHG reduction stated under SB 1383, an estimated 420 additional projects (50% AMMP technologies and 50% digesters) will be necessary to reduce 4.4 MMT CO_2e (California Air Resources Board (CARB), 2022b). Given the success observed to this point, there is the potential for the industry to achieve its 2030 climate goals and these scenarios to be accomplished. For additional consideration, it is important to note that approximately one-fifth of all California dairies have either constructed or are planning to build a privately financed or public-private partnership digester. Our case study is not able to perform sensitivity analysis on the likelihood of those other approximately 80% of the state's farms adopting dairy digesters. Although government and private market incentives have helped facilitate dairy digester adoption, this study would need additional data collection into farm behavior to understand these motivators for anaerobic digester adoption (Cowley and Wade Brorsen, 2018; California Air Resources Board (CARB), 2022a). Beyond 2030, further emission reductions are needed through farms adopting feed additives and digesters to help the industry offset its historical GHG emissions and continue to maintain climate neutrality.

CLIMATE NEUTRALITY FOR THE U.S. AND GLOBAL DAIRY INDUSTRY

Although California dairy can play a big role in producing climate-neutral milk, the majority of GHG emissions fall outside the scope of the state's dairy industry with >80% of the national herd located in other states of the U.S. (Macdonald *et al*., 2020). A recent publication looked at the U.S. dairy industry's ability to achieve climate neutrality given an assumed annual 1–2% reduction in industry-wide emissions (Place and Mitloehner, 2021). This scenario predicted U.S. dairy could achieve climate neutrality by 2041. While California will play a big role in helping meet these scenarios, other states are likely to follow suit in mandating dairy industry emission reductions and providing incentives to help producers adopt these practices (Liu *et al*., 2021). States whereby the dairy cow population has matured over the last couple of decades (e.g. New York and Pennsylvania) could more easily achieve climate neutrality under GWP* using the CH_4 reduction technologies compared to states with expanding dairy cow herds (e.g. Idaho and Texas) (USDA, 2022). To achieve state-specific climate neutrality, the latter will need greater reductions in CH_4 emissions.

As animal-source protein consumer demand continues to increase worldwide and especially in developing nations, this supply will likely be met with expanding herd sizes (Alexandratos and Bruinsma, 2012). This will result in increased CH_4 emissions and an increase in the global dairy industry's warming impact under GWP* (Allen *et al*., 2018; Liu *et al*., 2021; Smith *et al*., 2021). Although the global dairy industry has greatly reduced country-specific CH_4 intensities of milk production (kg milk/CH_4 emissions), mitigation technologies will need to be adopted to reduce total CH_4 emissions (FAO, 2018). Anaerobic digesters have already been shown to reduce CH_4 emissions, offset fossil fuel use, and provide a consistent and reliable form of energy. For example, the Indian dairy sector has rapidly implemented anaerobic digesters that reduced manure management CH_4 emissions by 19.12 MMT CO_2e (84%) from 1990 to 2022 (Bosoli *et al*., 2019). Anaerobic digesters have also been susceptible to CH_4 leakage and have increased the CH_4 footprint per kg of milk on farms where they have been implemented in the developing world (Bruun *et al*., 2014; York *et al*., 2017). Although the European Union has been a rapid adopter of anaerobic digesters, most of the substrates utilized are biofuel crops and the manure management CH_4 emission reductions have been outpaced by the herd size reduction observed from 1990 to 2020 (European Environment Agency, 2022). By implementing strong, aggressive reductions in CH_4 emissions as outlined in these scenarios, the California dairy sector can serve as a model to reduce the global dairy industry's impact on atmospheric warming. To make this happen, policymakers in California and around the world will be increasingly required to balance the need to meet the world's growing demand for milk and positively impact rural communities in a climate smart way (Rojas-Downing *et al*., 2017; Lane *et al*., 2019).

Conclusion

California dairy's GHG footprint is highly biased toward CH_4 emissions from enteric and manure management sources. By aggressively decreasing CH_4 emissions and utilizing GWP* to account for the industry's true warming impact, the present study demonstrates that the California dairy industry has the potential to contribute no additional annual warming and achieve climate neutrality before the end of the decade. Achieving the 40% reduction in manure management CH_4 emissions, set out under SB 1383, is enough to help the industry achieve climate neutrality. Climate-negative warming (or cooling) continues onwards through 2030 and helps the industry offset historical emissions. Continued reductions in CH_4 emissions will be necessary for climate neutrality to be achieved by California dairy to offset annual CO_2 and N_2O emission contributions. For California and the global dairy industry, there is the opportunity to achieve climate neutrality through a range of policies and technology programs to create a climate-compatible dairy sector.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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