Pathway to Climate Neutrality for U.S. Beef and Dairy Cattle Production

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Introduction

Net zero has been an increasingly popular topic in agriculture, the business community, and society at large. But, how should net zero apply to the beef and dairy sectors in the United States?

The Intergovernmental Panel on Climate Change defines net zero emissions in the following way (IPCC, 2019):

> *Net zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple greenhouse gases are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).*

For many public commitments from governments, corporations, and industries, the specific time horizon is often 2050 relative to an earlier date (e.g., 2018). Specifically, the Paris Agreement has a goal to limit global warming to well below 2 degrees Celsius, preferable to 1.5, compared to pre-industrial levels (UNFCCC, 2021). The Paris Agreement is unique compared to past global climate agreements such as the Kyoto Protocol that centered on greenhouse gas (GHG) emissions targets. Rather than GHG emissions targets, the Paris Agreement focuses on temperature change. Consequently, it is important that climate metrics are fit-for-purpose in representing temperature change impacts across future emissions scenarios. In other words, we should quantify GHG emissions by how they impact temperature over time.

In beef and dairy cattle production, the choice of climate metric (e.g., GWP_{100} or GWP_{20}) is particularly important, as most greenhouse gas emissions arising from the live cattle production phases of beef and milk foods, are the non-CO_2 gases – methane (CH_4) and nitrous oxide (N_2O). The choice of metric for the short-lived gas, CH_4, is especially important.

The most widely used metric today is the Global Warming Potential (GWP_{100}) with the unit of carbon dioxide equivalents (CO_2e). Carbon dioxide equivalents are calculated by taking the mass of the gas emitted and multiplying it by the gas' 100-year global warming potential (GWP_{100}) value. The IPCC Assessment Report (AR5) GWP_{100} values[1] for CO_2, CH_4, and N_2O are 1, 34, and 298, respectively (Myhre et al., 2013). Recent research has demonstrated that the widely used GWP_{100} for CH_4 poorly represents the impact of CH_4 emissions on global temperature change when emissions are stable or falling (**Figure 1**; Smith et al., 2021;) as it fails to account for the atmospheric removal of methane. Thus, the aggregation of all GHG emissions using GWP_{100} results in cumulative CO_2e emissions, which don't necessary represent the magnitude of future global surface temperature outcomes (Forster et al., 2021). As the cattle industries strive to cut emissions rates of CH_4 in the future, accurate climate metrics are of critical importance to clarify the degree of CH_4 emissions reductions required to achieve no additional warming and beyond.

The new IPCC Assessment Report (AR6) makes clear that if metrics account for the differences in CO_2 and short-lived climate pollutants, goals of halting temperature increases can be met by achieving net zero CO_2 emissions combined with stable or gently declining emissions of short-lived climate pollutants such as CH_4 (Arias et al., 2021).

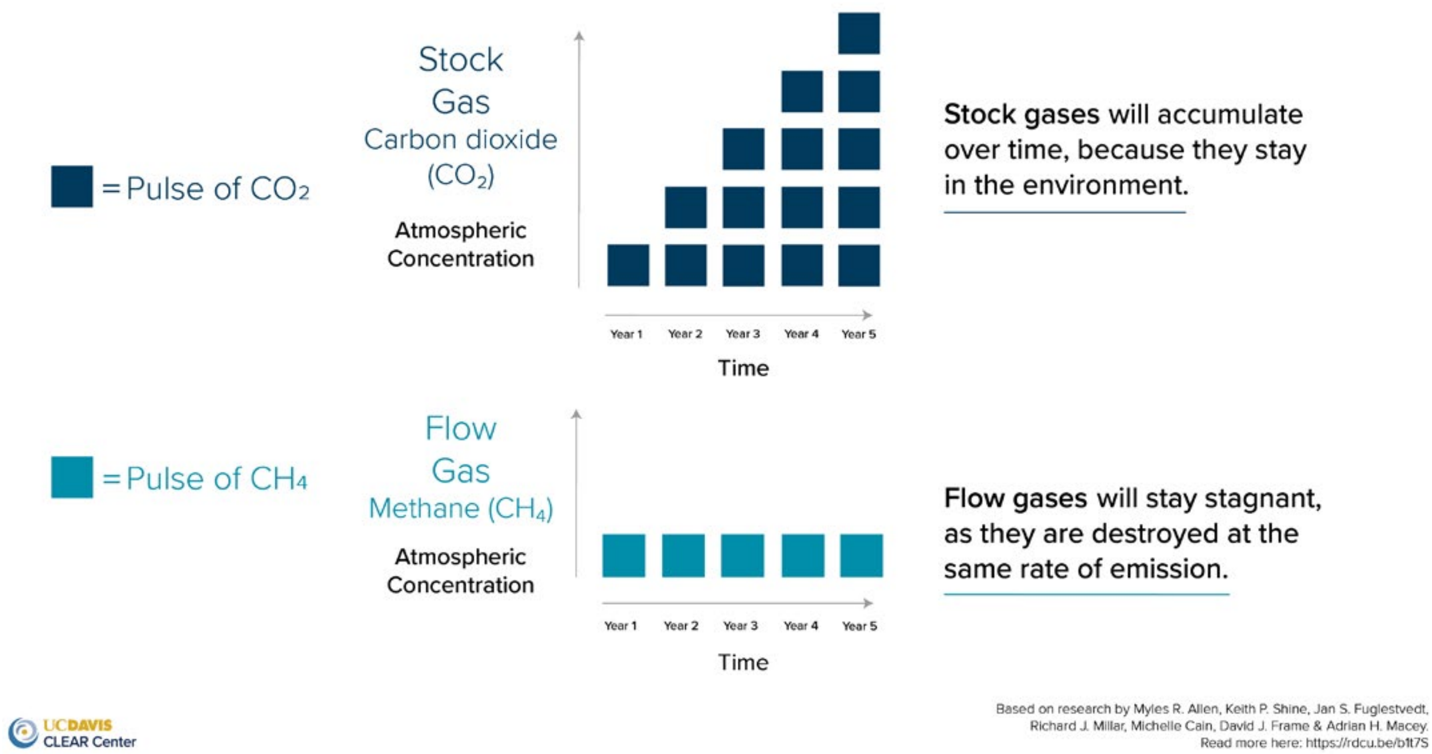

Figure 1. *Representation of the difference in atmospheric concentration responses for a scenario of constant annual emissions between long-lived, stock gases such as CO_2 and short-lived, flow gases such as CH_4. Adapted from Allen et al., 2018.*

[1] *The GWP_{100} values for CH_4 and N_2O listed here include climate-carbon feedbacks and can be found in Table 8.7 of Myhre et al., 2013. Without climate carbon feedbacks, the GWP_{100} values from AR5 are 28 and 265 for CH_4 and N_2O, respectively.*

Carbon dioxide warming equivalents

To overcome the challenges of using GWP_{100} in stable or falling emissions scenarios for short-lived climate pollutants, such as CH_4, a new metric, GWP* (GWP star) has been proposed (Allen et al., 2018). GWP* considers the change in CH_4 emissions rates over a specified time frame (typically, 20 years for CH_4) and the small stock component to calculate carbon dioxide warming equivalent (CO_2we) emissions. The following equation from Smith et al. (2021) can be used to calculate CO_2we emissions:

$$CO_{2we} = 4.53 * E100(t) - 4.25 * E100\ (t\text{-}20)$$

Where, E_{100} are the CO_2e emissions calculated using GWP_{100}, t is the year for which the CO_2we are being calculated, and t-20 are the emissions in CO_2e emissions calculated using GWP_{100} twenty years prior.

For longer lived gases, such as N_2O, GWP_{100} adequately represents warming responses to emissions rate increases or decreases, and the GWP_{100} value can be used to calculate CO_2we for those gases.

GWP* also highlights how increases in methane emissions rates can lead to increases in warming more accurately than GWP_{100}. To illustrate this, we can examine U.S. EPA data on CH_4 and N_2O emissions that result from U.S. dairy cattle and their managed manure (U.S. EPA, 2021).

Trends in direct greenhouse gas emissions from US dairy and beef cattle

Total direct greenhouse gas emissions from the U.S. dairy industry have increased since 1990, with enteric CH_4 emissions increasing 11%, manure CH_4 emissions increasing 119%, and manure N_2O emissions increasing 16% (**Figure 2**). Important context for these emissions trends is the changes in milk production and in dairy farm size and manure management systems.

From 1990 to 2019, the number of dairy cows in the United States decreased 6%, but milk production per cow increased 56%, translating into an increase in annual milk production in the U.S. by 70.7 billion pounds of milk.

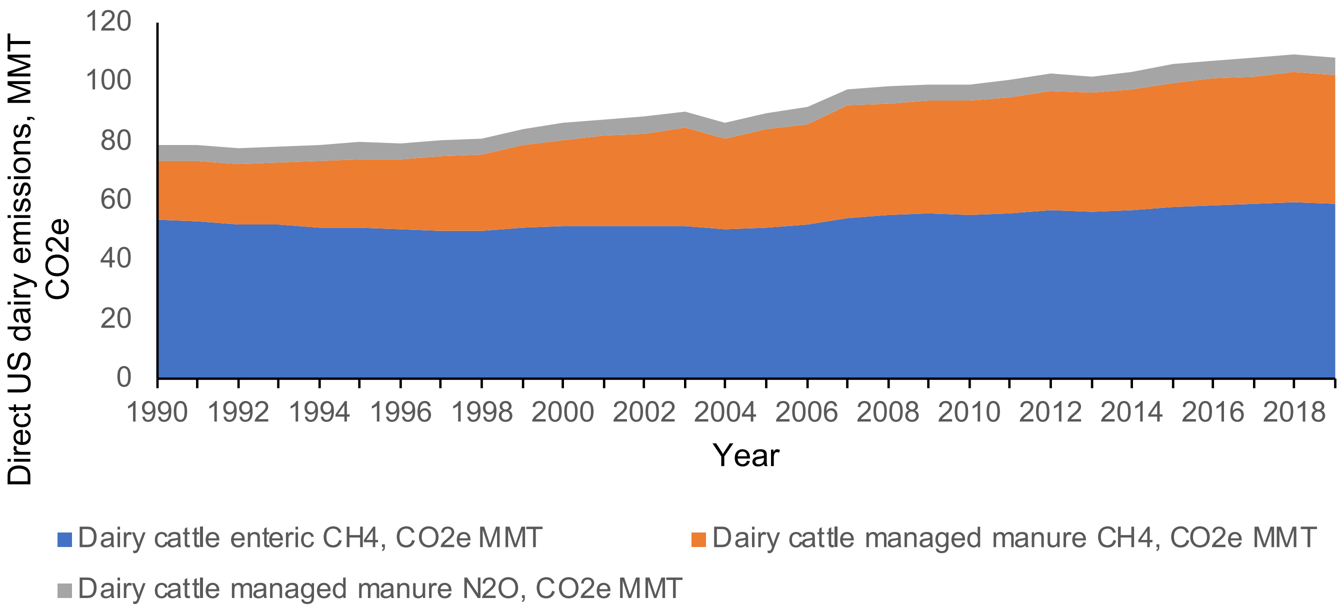

Figure 2. *Trends in absolute direct greenhouse gas emissions from the U.S. dairy industry from 1990 to 2019 according to U.S. Environmental Protection Agency using IPCC AR5* GWP_{100} *values of 34 and 298 for* CH_4 *and* N_2O*, respectively.*

Carbon neutral, climate neutral, and net zero – what do these terms mean?

The IPCC (2021) defines **carbon neutral** as the condition in which anthropogenic CO_2 emissions associated with a subject are balanced by anthropogenic CO_2 removals. The subject can be an entity such as a country, an organization, a district or a commodity, or an activity such as a service and an event. Carbon neutrality is often assessed over the life cycle including indirect (i.e., "scope 3") emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme.

Net zero CO_2 emissions are defined by the IPCC (2021) as the condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period. At a global scale, the terms carbon neutrality and net zero CO_2 emissions are equivalent. At sub-global scales, net zero CO_2 emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while carbon neutrality generally includes emissions and removals within and beyond the direct control or territorial responsibility of the reporting entity (e.g., life cycle emissions).

Net zero GHG emissions are defined as by the IPCC (2021) as the condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions associated with a subject are balanced by metric-weighted anthropogenic GHG removals. The subject can be an entity such as a country, an organization, a district or a commodity, or an activity such as a service and an event. GHG neutrality is often assessed over the life cycle including indirect (i.e., "scope 3") emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme. The quantification of GHG emissions and removals depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

Climate neutrality is not formally defined by the IPCC; however, in common usage it can be viewed as equivalent to achieving no additional climate impact from activities from an entity at the regional, sub-national, or national scale (Pineda and Faria, 2019). Climate neutrality can be viewed as equivalent to net zero warming and can be characterized by achieving and maintaining net emissions at 0 CO_2 warming equivalents.

Net zero warming is not formally defined by the IPCC; however, it has been described by Cain et al. (2019) as net zero (emissions plus removals) CO_2 warming equivalent emissions as calculated using GWP* for short-lived climate pollutants such as CH_4. Net zero warming implies activities from an entity at the regional, sub-national, or national scale would not lead to additional warming, and could be defined by reaching and maintaining net 0 CO_2 warming equivalent emissions.

The EPA estimates enteric CH_4 emissions from cattle using the Cattle Enteric Fermentation Model (CEFM) that makes assumptions about the animal's feed intake, the digestibility of feeds, and the CH_4 yield per unit of gross energy the animal consumes. As U.S. dairy cattle have increased their productivity, they have increased feed consumption. Feed consumption is a key driver of CH_4 emissions, thus enteric CH_4 emissions per cow in the U.S. have increased. However, enteric CH_4 emissions per lb. of milk have declined as increases in CH_4 emissions per cow have been offset by increased milk production. Solutions that further decouple milk production from CH_4 production, such as improvements in feed efficiency and enteric methane inhibitors, can help stabilize and decrease total enteric CH_4 emissions coming from the U.S. dairy industry.

Conversely, CH_4 emissions from manure management systems have increased per lb. of milk. This has been driven by a shift in production systems of dairy farms with smaller herd sizes where manure is managed as a solid (e.g., daily spreading of manure), to dairy farms with larger herd sizes and manure managed in liquid systems (e.g., anaerobic lagoons). As CH_4 production requires an oxygen-free environment, the switch to more long-term storage, liquid manure management systems has increased the yield of CH_4 gas from dairy cattle manure in the United States.

Figure 3 shows how increasing methane emissions from the dairy industry from 1990 through 2019 increase the assumed warming impacts coming from the U.S. dairy industry when expressed in CO_2we (Panel B) relative to CO_2e (Panel A). Cumulatively[2] , the direct emissions from 2010 to 2019 from the U.S. dairy industry were 1047 million metric tons (MMT) of CO_2e and 1377 MMT of CO_2we. Using GWP* increases the assumed warming impact of the U.S. dairy industry in this time frame by 32%.

[2] Cumulative emissions refer to the sum of annual emissions of greenhouse gas emissions expressed as CO2e or CO2we for the 2010 to 2019 period. See Figure 5 for a representation of cumulative emissions from 2010 to 2050 from US dairy cattle production.

The US beef industry's direct greenhouse gas emissions profile is different from dairy. Enteric CH_4 emissions represent a larger percent of the total direct emissions for beef vs. dairy. For example, in 2019, enteric CH_4 emissions were 93% (of the total) of the beef cattle industry's direct GHG emissions, while in dairy they were 54%. The different emission profiles can be explained by the larger number of beef vs. dairy cattle (80 million vs. 14 million, respectively, on January 1st 2019 according to USDA NASS data), and differences in how manure is managed between the two industries. Unlike dairy, very few liquid manure management systems exist in the U.S. beef industry, rather manure is typically either deposited on pasture or rangelands where cattle are grazing, or in drylot systems at feedyards where cattle are finished on grain-based diets. Consequently, the U.S. beef industry's warming impact is determined in larger part by changes in enteric CH_4 emissions as **Figure 4** demonstrates.

In January 2010, there were 80.4 million cattle excluding dairy cows and heifers in the U.S., and by January 2014, that number had dropped to 74.5 million cattle (USDA NASS, 2021). This decrease in the beef cattle inventory was largely driven by a historic drought in the Southern Great Plains region of the U.S. that is home to both cow-calf operations and feedyards. The decline in enteric CH_4 emissions driven by herd size reduction resulted in cumulative[3] CO_2we emissions of 208 MMT as compared to 1791 MMT of CO_2e in the decade of 2010 - 2019. In this falling emissions scenario, using GWP_{100} leads to an overestimation of the warming impact of beef cattle's direct greenhouse gas emissions by 88%.

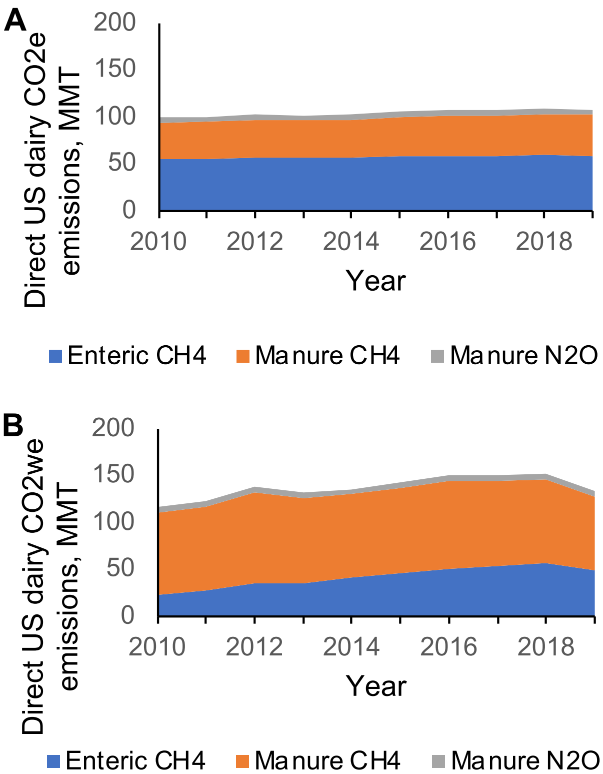

Figure 3. *Direct greenhouse gas emissions from the U.S. dairy industry from 2010 to 2019 expressed as carbon dioxide equivalents (CO_2e; Panel A) and carbon dioxide warming equivalents (CO_2we; Panel B).*

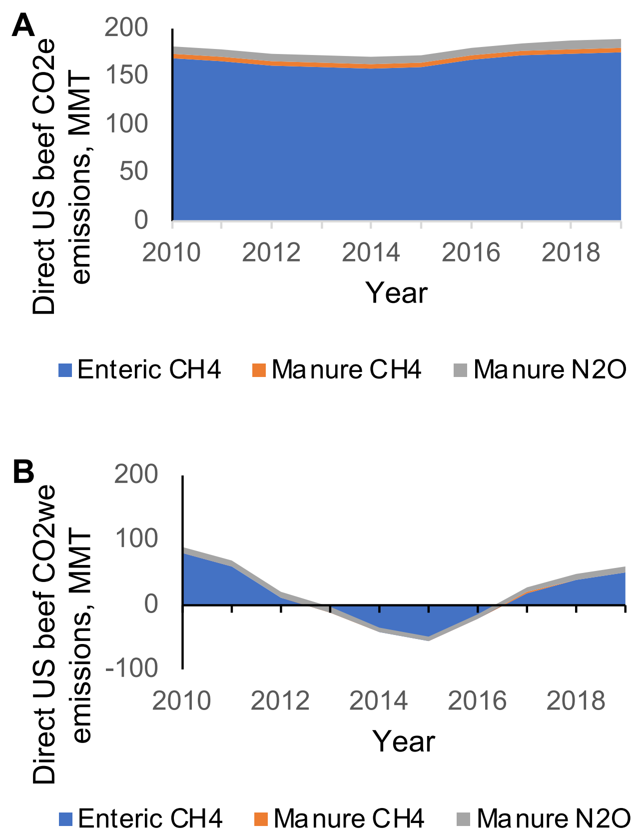

Figure 4. *Direct greenhouse gas emissions from the U.S. beef cattle industry from 2010 to 2019 expressed as carbon dioxide equivalents (CO_2e; Panel A) and carbon dioxide warming equivalents (CO_2we; Panel B).*

The path to climate neutrality or net zero warming for U.S. beef and dairy cattle production

Increasingly, corporations and industries are making pledges to achieve net zero emissions from beef and dairy production. When these emissions pledges are expressed as net zero CO_2e, the path

[3] *Cumulative emissions refer to the sum of annual emissions of greenhouse gas emissions expressed as CO_2e or CO_2we for the 2010 to 2019 period. See figure 6 for a representation of cumulative emissions from 2010 to 2050 for U.S. beef cattle production.*

to achieve these commitments may be difficult, as this will require balancing CO_2e emissions with soil carbon stock increases through increased carbon sequestration from the whole industry.
For example, it was estimated that the U.S. beef cattle production system emitted 243 MMT annually of CO_2e from 2013 to 2017, which is inclusive of the direct and indirect (feed production, fertilizer inputs, electricity use, etc.) greenhouse gas emissions sources (Rotz et al., 2019). Consider a scenario where indirect emissions, such as energy used or feed production, from beef cattle production were zeroed out. This would require adoption of non-CO_2 emitting energy sources and significant changes to feed production to lower greenhouse gas emissions and likely increase soil carbon stocks to offset residual emissions, such as N_2O emissions resulting from N inputs (manure and fertilizer) on grazing and feed production acres. If manure and enteric emissions were also lowered 40% across all 80+ million beef cattle in this hypothetical scenario, beef cattle would still emit 87 MMT of CO_2e annually[4]. These unavoidable residual emissions would need to be offset by 87 MMT of additional soil carbon stocks expressed as CO_2e each year to achieve a net zero CO_2e emissions balance.

From a temperature response perspective, a net zero CO_2e emissions balance from the U.S. cattle industries would likely exceed a goal of climate neutrality (no additional warming impacts) from the industry and lead to climate positive production (equivalent to removing CO_2 from the atmosphere). Achieving such a balance would be unnecessary for U.S. beef cattle production if the initial goal is to no longer add warming to the atmosphere within the next 20 to 30 years, especially in a cost-effective manner. Declining methane emissions to smaller, but still positive values can cause a decline in warming (Forster et al., 2021). Furthermore, it would be nearly impossible for the sector to achieve net zero CO_2e. Make no mistake this is not “greenwashing,” or an attempt to lighten the climate load of the U.S. beef – or dairy sector – reaching climate neutrality is a goal many CO_2-producing sectors stand by when they aim to be net-zero carbon.

The ability to reach net zero warming, or a net zero CO_2we emissions balance is more achievable; however, accomplishing such a goal will still require major reductions in emissions from business-as-usual U.S. beef and dairy cattle production. Net zero warming or climate neutrality would align to the Paris climate agreement’s temperature change goal.

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[4] *Using the GWP_{100} values of 28 and 265 for CH_4 and N_2O, respectively, as was used in Rotz et al., 2019.*

There could be many iterations of a pathway to net zero warming by 2050 for U.S. beef and dairy production but let us consider a specific case study for each industry to make this concept more tangible.

For both scenarios outlined in the **Tables 1** and **2** below, it is assumed that the beef and dairy cattle herds will remain stable from the January 1, 2021, herd size reported by USDA through 2050. It is also assumed that the beef and dairy sectors will manage to reduce direct and indirect emissions, such as utilizing feed additives to reduce enteric emissions or moving away from CO_2 emitting energy sources. **Figure 5** shows the annual CO_2we emissions from U.S. beef and dairy cattle production, with the combined industries CO_2we emissions reaching zero in 2044 given the emissions scenarios analyzed. **Figures 6 and 7** provide more context on the emissions scenarios for both species and highlight the cumulative emissions from 2010 to 2050 in both CO_2e and CO_2we emissions. Net zero warming is achieved when the cattle production activities do not add additional CO_2we emissions to the total. This means in these scenarios, both U.S. beef and dairy cattle production would add to warming in the near term, but once annual CO_2we emissions reach zero and are maintained at or below that level, the industries would not contribute to warming thereafter.

In both scenarios outlined, emissions need to decline per lb. of beef and milk produced, but also on an absolute basis, meaning the total emissions from the cattle industries must decline. As was aforementioned, this would be a departure from the trends of the past 30 years according to U.S. EPA data. Additionally, in these scenarios, beef and milk production expands, which is important to continue to meet U.S. consumer demands, along with growing export markets. As the population continues to grow globally and beef and dairy are important sources of high-quality protein and micronutrients to the human diet, achieving net zero warming while still increasing total output will be valuable.

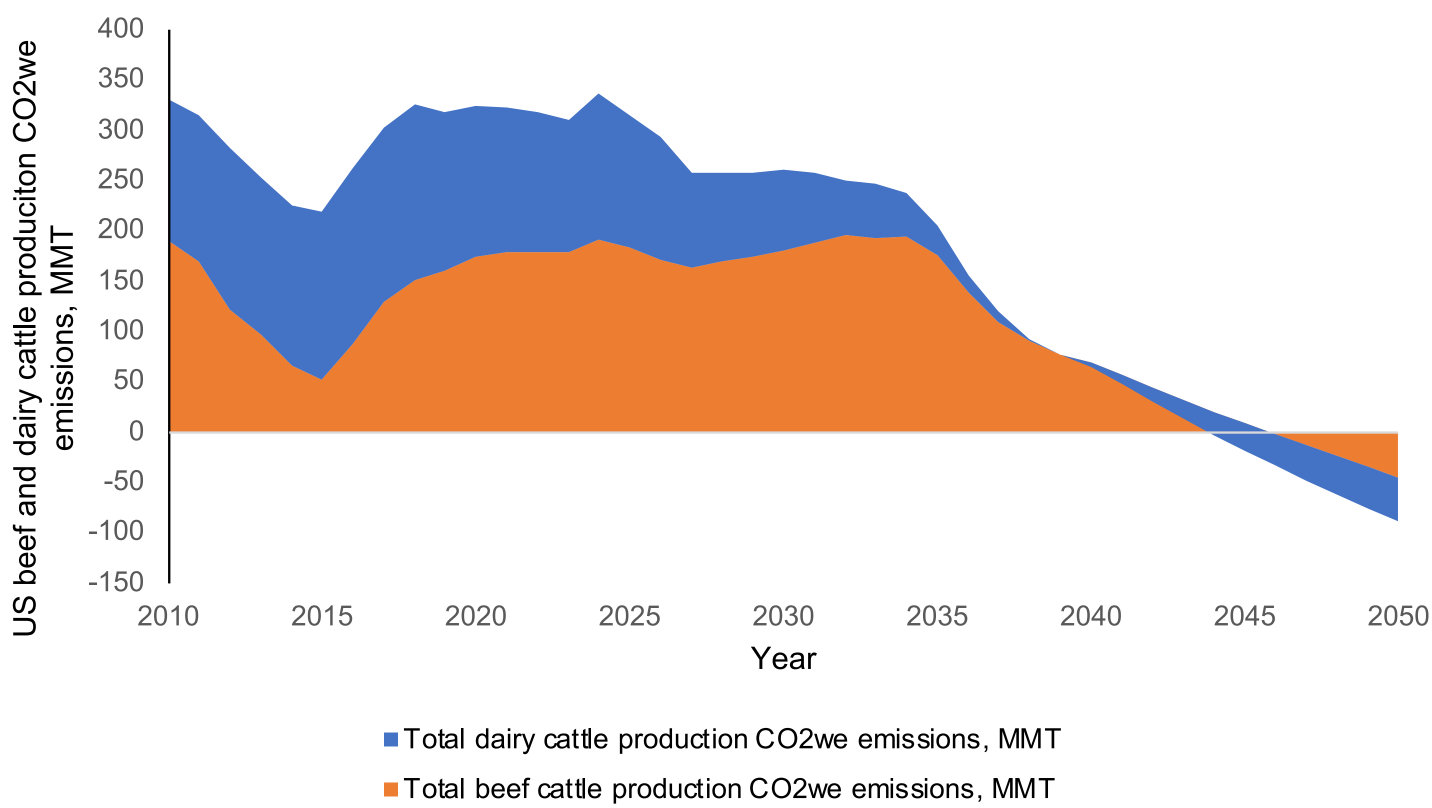

Figure 5. *Annual U.S. beef and dairy cattle production cradle-to-farm gate CO_2we emissions expressed as MMT from 2010 to 2050 for the case study scenarios. Achieving reductions in emissions as outlined in Figures 6 and 7 results in 2050 emissions from U.S. beef and dairy cattle production of -89 MMT of CO_2we, meaning that no additional warming would occur from cattle production activities in that year.*

Item	YEAR				2050 % change from 2020
	2020	2030	2040	2050	
Number of dairy cows, Jan. 1st	9,342,600	9,440,000	9,440,000	9,440,000	1%
Milk production per cow, lbs./year	23,893	27,187	30,935	35,200	+47%
Total milk production, billion lbs.	223.2	256.7	292.0	332.3	+49%
Indirect GHG emissions, kg CO_2e/kg milk	0.233	0.195	0.155	0.112	-52%
Cradle-to-farm gate footprint, kg CO_2e/kg milk[5]	1.30	1.10	0.87	0.67	-48%
Mean enteric CH_4 emissions for U.S. dairy cows, g/cow/d	404	400	361	311	-23%
Absolute enteric CH_4 emissions, MMT of CO_2e	58.8	58.7	54.2	48.3	-18%
Absolute manure CH_4 emissions, MMT CO_2e	43.4	40.5	34.8	30.0	-31%
Absolute CO_2e emissions, MMT	131.7	128.0	115.7	101.2	-23%
Absolute CO_2we emissions, MMT	149.8	80.5	-4.06	-43.9	-129%

Table 1. *Case study scenario for U.S. dairy cattle production to achieve net zero warming in 2050 relative to a base year of 2020. Carbon dioxide equivalent (CO_2e) emissions are calculated using the 100-year global warming potentials of 34 and 298 for methane (CH_4) and nitrous oxide (N_2O), respectively..*

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[5] *The cradle-to-farm gate estimated here does not allocate any enteric and manure emissions from dairy cattle in the EPA GHG inventory to beef production. For comparison, a recent footprint analysis from Capper and Cady, 2020 estimated a dairy cattle footprint of 1.7 kg CO_2e/kg milk using GWP_{100} values of 34 and 298 for CH_4 and N_2O, respectively. Thoma et al. (2013) reported a cradle-to-farm gate U.S. dairy average of 1.23 kg CO_2e/kg fat-and-protein corrected milk (FPCM) using the GWP_{100} values of 25 and 298 for CH_4 and N_2O, respectively. Rotz et al. (2021) reported a U.S. dairy footprint of 1.01 kg CO_2e/kg FPCM using the GWP_{100} values of 28 and 265 for CH_4 and N_2O, respectively.*

Item	YEAR				2050 % change from 2020
	2020	2030	2040	2050	
Total non-dairy cattle, Jan. 1st	79,766,700	79,549,600	79,549,600	79,549,600	-0.3%
Cattle on feed, Jan. 1st	14,657,700	14,707,400	14,707,400	14,707,400	+0.3%
Cattle not on feed Jan. 1st	65,109,000	64,842,200	64,842,200	64,842,200	-0.4%
Beef production, lbs. per live animal	289	304	319	334	+16%
Total beef production, billion lbs.	27.0	28.4	29.8	31.2	+15%
Indirect GHG emissions, kg CO_2e/kg beef carcass weight	8.28	7.60	6.55	5.11	-38%
Cradle-to-farm gate footprint, kg CO_2e/kg beef carcass weight[6]	23.72	22.26	19.28	15.70	-34%
Mean enteric CH_4 emissions from U.S. cattle on feed, g/animal/d	127	123	111	95.8	-24%
Mean enteric CH_4 emissions from U.S. beef cows, g/animal/d	263	263	238	204	-22%
Absolute enteric CH_4 emissions, MMT of CO_2e	175.5	175.0	158.2	136.0	-23%
Absolute CO_2e emissions, MMT	291.3	286.9	260.8	222.4	-24%
Absolute CO_2we emissions, MMT	174.8	180.7	69.24	-45.09	-126%

Table 2. *Case study scenario for U.S. beef cattle production to achieve net zero warming in 2050 relative to a base year of 2020. Carbon dioxide equivalent (CO_2e) emissions are calculated using the 100-year global warming potentials of 34 and 298 for methane (CH_4) and nitrous oxide (N_2O), respectively.*

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[6] *The carbon footprint here does not allocate emissions to or from dairy cattle, but rather only accounts for enteric and manure emissions directly attributed to non-dairy cattle within the U.S. EPA GHG inventory. For comparison, Rotz et al. (2019) found a U.S.-wide carbon footprint for beef cattle production of 21.3 kg CO_2e/kg carcass weight using GWP_{100} values of 28 and 265 for CH_4 and N_2O, respectively. The 2020 footprint reported here would be 21.04 kg CO_2e/kg carcass weight using those GWP_{100} values.*

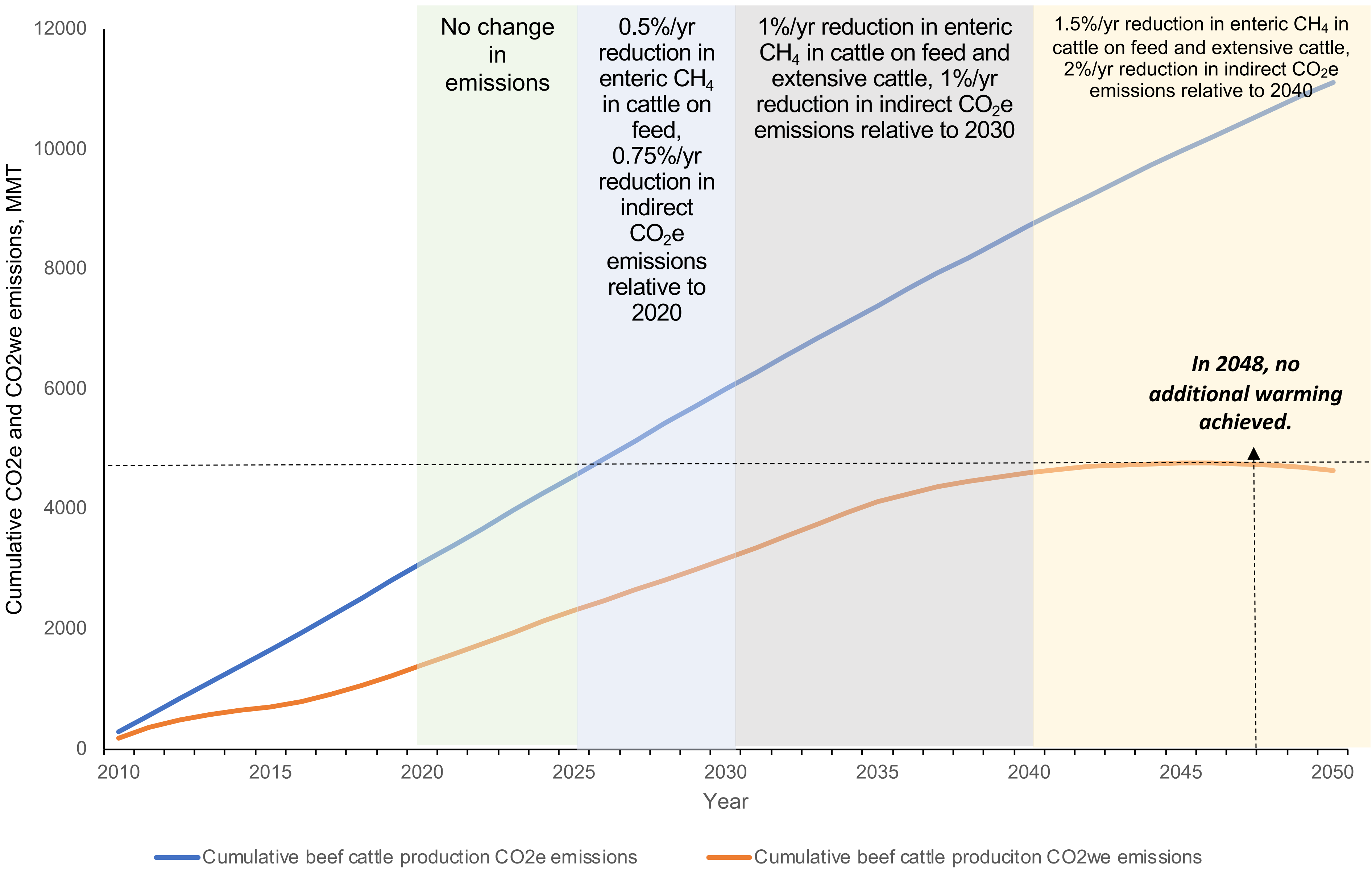

Figure 6. *Cumulative carbon dioxide equivalent (CO_2e) or carbon dioxide warming equivalent (CO_2we) for U.S. dairy cattle production from 2010 to 2050 for the case study scenario. Assumed changes in emissions by time period are indicated on the graph. The point at which annual CO_2we emissions do not add to further warming is indicated on the graph.*

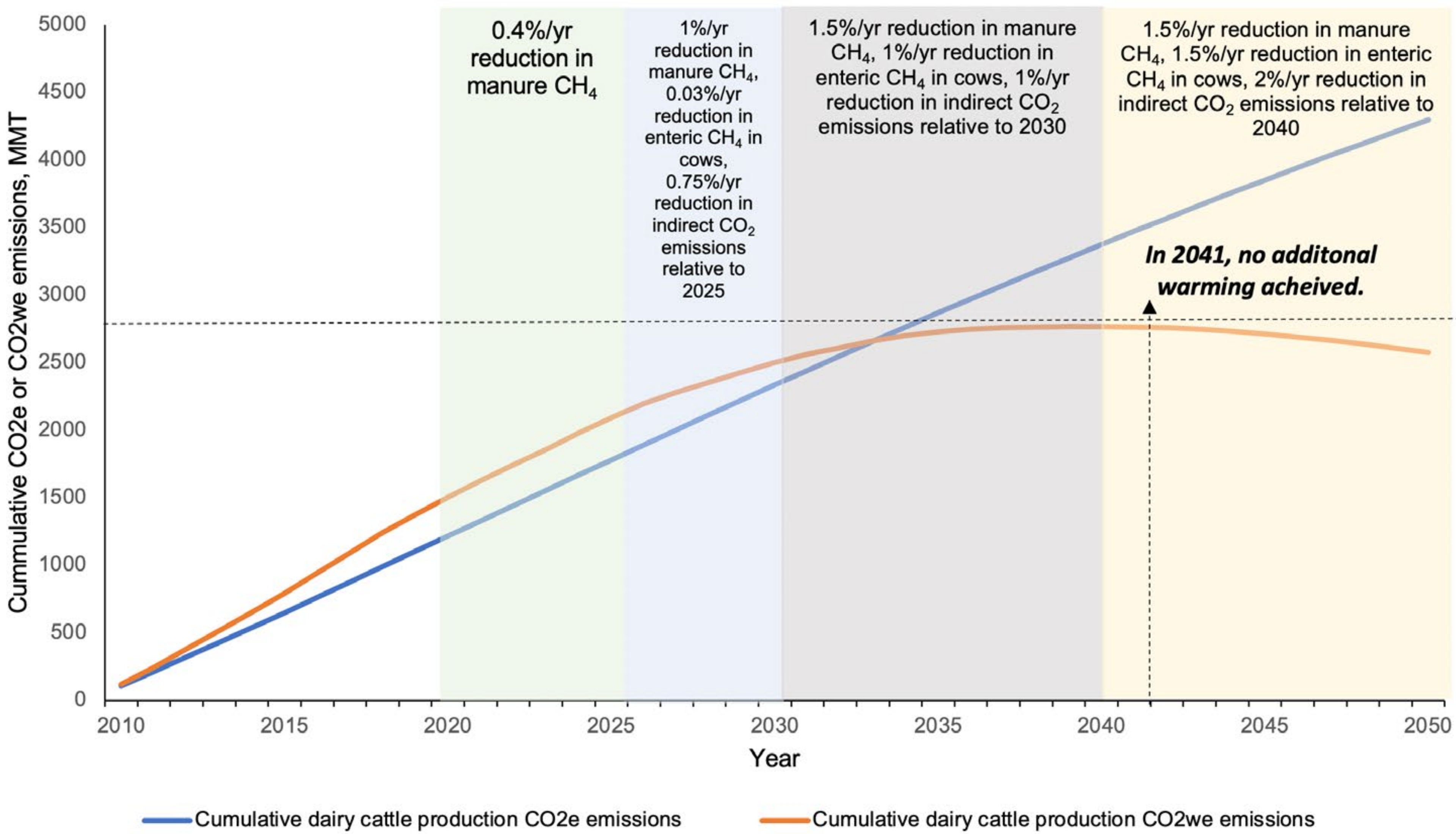

Figure 7. *Cumulative carbon dioxide equivalent (CO_2e) or carbon dioxide warming equivalent (CO_2we) for US beef cattle production from 2010 to 2050 for the case study scenario. Assumed changes in emissions by time period are indicated on the graph. The point at which annual CO_2we emissions do not add to further warming is indicated on the graph.*

Explore and experiment with the data used in these case studies: https://clear.ucdavis.edu/news/climate-neutrality

Both scenarios require reducing enteric CH_4 emissions per animal, which is counter to the prevailing trend of the past 30 years as emissions per head have grown with increasing productivity of beef and dairy cattle in the U.S. Thus, while the emission reductions to achieve net zero warming will not be as large as what is required to achieve net zero CO_2e emissions, they are still substantial departures from business-as-usual and will require development and adoption of new innovations. Of particular importance is development of solutions to lower enteric CH_4 emissions in extensively managed (e.g., grazing) cattle. As the bulk of CH_4 emissions from beef cattle production come from cattle on pastures and not those in feedyards (82% of beef cattle), delivering feed additives, developing low-CH_4 emitting breeding strategies, and/or other innovations will be required.

For dairy production, enteric and manure CH_4 emissions reductions will be critical. New manure management techniques, such as anaerobic biogas digesters are one such strategy that is growing in importance in California. Indeed, the dairy industry within the state has already achieved a 25% reduction in manure CH_4 emissions since 2013. Thus, the estimated reductions within the case study scenario are likely highly technically feasible but will require the right incentives or policies to achieve. It is also assumed that the cattle industries will be able to reduce the indirect CO_2e emissions from feed production and other inputs per lb. of milk or beef produced. This could include moving to more non-CO_2 emitting energy sources, reducing N_2O emissions from feed production, or increasing soil carbon stocks to offset CO_2e emissions.

Conclusions

As the climate crisis is upon us, it will be critical for all components of the U.S. economy to do their part to stabilize the climate and stay within 1.5 to 2 degrees Celsius temperature change globally. The U.S. beef and dairy cattle industries are no different. However, it will be paramount to use metrics that are fit-for-purpose if the goal is not contributing to additional warming. As the cattle industries' emissions profiles are dominated by short-lived, high radiative forcing CH_4 emissions, the U.S. cattle industries should set emissions reductions goals and targets on a basis of achieving net zero warming defined as 0 CO_2 warming equivalent emissions, rather than net zero as defined by 0 CO_2 equivalent emissions. As outlined in the case study scenarios, beef and dairy cattle production that no longer contributes to warming in 2050 could be achieved by lowering CH_4 emissions by 18-32% in the coming decades depending upon the species and source. However, these reductions only achieve net zero warming when also coupled with substantial reductions in emissions of CO_2 and N_2O from feed production, land use, and energy use and other inputs. For transparency and educational purposes, readers are encouraged to use the spreadsheet behind these calculations to explore the range of possible scenarios that would yield net zero warming as defined by 0 annual CO_2 warming equivalent emissions. Business-as-usual will not allow the U.S. beef and dairy industries to achieve net zero warming; however, it is within reach as new and existing innovations that lower GHG emissions become more widely available, and adoption of those innovations are incentivized.

References

Allen, M.R., Shine, K.P., Fuglestvedt, J.S., Millar, R.J., Cain, M., Frame, D.J., & Macey, A.H. 2018. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. npj Climate and Atmospheric Science. 1(16). Available at: https://www.nature.com/articles/s41612-018-0026-8 accessed July 21, 2021.

Arias, P. A., N. Bellouin, E. Coppola, R. G. Jones, G. Krinner, J. Marotzke, V. Naik, M. D. Palmer, G-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P. W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R. P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J. G. Canadell, C. Cassou, A. Cherchi, W. Collins, W. D. Collins, S. L. Connors, S. Corti, F. Cruz, F. J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F. J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J. S. Fuglestvedt, J. C. Fyfe, N. P. Gillett, L. Goldfarb, I. Gorodetskaya, J. M. Gutierrez, R. Hamdi, E. Hawkins, H. T. Hewitt, P. Hope, A. S. Islam, C. Jones, D. S. Kaufman, R. E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J-Y. Lee, J. Li, T. Mauritsen, T. K. Maycock, M. Meinshausen, S-K. Min, P. M. S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A. C. Ruane, L. Ruiz, J-B. Sallée, B. H. Samset, S. Sathyendranath, S. I. Seneviratne, A. A. Sörensson, S. Szopa, I. Takayabu, A-M. Treguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, K. Zickfeld, 2021,Technical Summary. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press

Cain, M., M. Allen, & J. Lynch. 2019. Net zero for agriculture. Available at: https://www.oxfordmartin.ox.ac.uk/publications/net-zero-for-agriculture/ accessed August 24, 2021.

Forster, P., T. Storelvmo, K. Armour, W. Collins, J. L. Dufresne, D. Frame, D. J. Lunt, T. Mauritsen, M. D. Palmer, M. Watanabe, M. Wild, H. Zhang, 2021, The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press

IPCC, 2021: Annex VII: Glossary [Matthews, J. B. R., J. S. Fuglestvedt, V. Masson-Delmotte, V. Möller, C. Méndez, R. van Diemen, A. Reisinger, S. Semenov (ed.)]. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

IPCC (Intergovernmental Panel on Climate Change). 2019. Special Report: Global Warming of 1.5˚C. Glossary. Available at: https://www.ipcc.ch/sr15/chapter/glossary/ accessed July 9, 2021.
Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pineda, A.C. & P. Faria. 2019. Towards a science-based approach to climate neutrality in the corporate sector. Discussion paper. Available at: https://sciencebasedtargets.org/resources/files/Towards-a-science-based-approach-to-climate-neutrality-in-the-corporate-sector-Draft-for-comments.pdf accessed August 24, 2021.

Rotz, C.A., Asem-Hiablie, S., Place, S., & Thoma, G. 2019. Environmental footprints of beef cattle production in the United States. Ag. Syst. 169: 1-13. https://doi.org/10.1016/j.agsy.2018.11.005

Smith, M.A., Cain, M. & Allen, M.R. 2021. Further improvement of warming-equivalent emissions calculation. npj Clim Atmos Sci 4, 19. https://doi.org/10.1038/s41612-021-00169-8

United Nations Climate Change (UNFCCC). 2021. The Paris Agreement. Available at: https://sciencebasedtargets.org/resources/files/Towards-a-science-based-approach-to-climate-neutrality-in-the-corporate-sector-Draft-for-comments.pdf accessed July 9, 2021.

United States Department of Agriculture National Agricultural Statistics Service (USDA NASS). 2021. Cattle. Available at: https://usda.library.cornell.edu/concern/publications/h702q636h accessed July 9, 2021.

United States Environmental Protection Agency (US EPA). 2021. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019. Available at: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019 accessed July 9, 2021.

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Dr. Sara E. Place is the chief sustainability officer at Elanco, where she provides customers with technical expertise on sustainability issues and supports Elanco's Healthy Purpose initiative.

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Frank is committed to making a difference for generations to come. As part of his position, he collaborates with the animal agriculture sector to create better efficiencies and mitigate pollutants. He is passionate about understanding and mitigating air emissions from livestock operations. In addition, he is focusing on the food production challenge that will become a global issue as the world's population grows to nearly 10 billion by 2050.

Frank received a Master of Science degree in animal science and agricultural engineering from the University of Leipzig, Germany, and a doctoral degree in animal science from Texas Tech University. Frank joined UC Davis in 2002, to fill its first-ever position focused on livestock and air quality.

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