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Galyean appreciation club review: a holistic perspective of the societal relevance of beef production and its impacts on climate change

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Abstract

This article provides a science-based, data-driven perspective on the relevance of the beef herd in the U.S. to our society and greenhouse gas (GHG) contribution to climate change. Cattle operations are subject to criticism for their environmental burden, often based on incomplete information disseminated about their social, economic, nutritional, and ecological benefits and detriments. The 2019 data published by the U.S. Environmental Protection Agency reported that U.S. beef cattle emitted 22.6% of the total agricultural emissions, representing about 2.2% of the total anthropogenic emissions of CO_2 equivalent (CO_2e). Simulations from a computer model developed to address global energy and climate challenges, set to use extreme improvements in livestock and crop production systems, indicated a potential reduction in global CO_2e emissions of 4.6% but without significant enhancement in the temperature change by 2030. There are many natural and anthropogenic sources of CH_4 emissions. Contrary to the increased contribution of peatlands and water reservoirs to atmospheric CO_2e, the steady decrease in the U.S. cattle population is estimated to have reduced its methane (CH_4) emissions by about 30% from 1975 to 2021. This CH_4 emission deacceleration of 2.46 Mt CO_2e/yr^2 might be even more significant than reported. Many opportunities exist to mitigate CH_4 emissions of beef production, leading to a realistic prospect of a 5% to 15% reduction in the short term after considering the overlapping impacts of combined strategies. Reduction strategies include feeding synthetic chemicals that inactivate the methyl-coenzyme M reductase (the enzyme that catalyzes the last step of methanogenesis in the rumen), red seaweed or algae extracts, ionophore antibiotics, phytochemicals (e.g., condensed tannins and essential oils), and other nutritional manipulations. The proposed net-zero concept might not solve the global warming problem because it will only balance future anthropogenic GHG emissions with anthropogenic removals, leaving global warming on a standby state. Recommendations for consuming red meat products should consider human nutrition, health, and disease and remain independent of controversial evidence of causational relationships with perceived negative environmental impacts of beef production that are not based on scientific data.

Lay Summary

This article aims to provide data-driven information about the relevance of the U.S. beef cattle herd to our society and its greenhouse gas (GHG) contribution to climate change. The Environmental Protection Agency reported that U.S. beef cattle emitted 22.6% of the total agricultural emissions, representing about 2.2% of the total anthropogenic emissions of carbon dioxide equivalent (CO_2e). Although the GHG contribution of the U.S. beef cattle production is small, there are many opportunities to reduce enteric methane emissions from beef cattle, with realistic estimates of a 5% to 15% reduction. However, net-zero emissions will be challenging to achieve for beef production. Considering the relatively minor contribution of beef cattle production to GHG emissions, other sources with a greater contribution to GHG emissions should be a much higher priority for mitigation as they would have a more substantial impact on slowing global warming. Recommendations by health professionals for consuming red meat products should consider human nutrition, health, and disease and remain independent of perceived negative environmental impacts of beef production that are not based on scientific data.

Key words: agriculture, animal science, environment, greenhouse gas, resilience, sustainability

Abbreviations: 3-NOP, 3-nitrooxypropanol; CO_2e, equivalent CO_2; ECCC, Environment and Climate Change Canada; En-ROADS, Energy-Rapid Overview and Decision Support; EPA, Environmental Protection Agency; FAO, Food and Agriculture Organization; GHG, greenhouse gas; GWP, global warming potential; Gt, Gigaton; IARC, International Agency for Research on Cancer; ILRI, International Livestock Research Institute; IPCC, Intergovernmental Panel on Climate Change; LCA, life-cycle assessment; Mt, Megaton; Tg, Teragram; UNEP, United Nations Environment Program; USDA, United States Department of Agriculture; USDHHS, U.S. Department of Health and Human Services; WHO, World Health Organization.

Introduction

The State of Food and Agriculture series by the Food and Agriculture Organization of the United Nations (FAO) confirms, year after year, that the role of livestock within agrifood systems in ameliorating global poverty, hunger, food insecurity, and malnutrition is incontestable (FAO, 2021). Livestock production represents 40% of the global value of agricultural output and provides livelihood support and food to approximately a billion people (FAO, 2009). Though dependence on livestock production varies widely among countries, its significance is irrefutable: livestock production accounts for between 7% and 31% of kilocalories and between 20% and 60% of protein consumption globally (FAO, 2006, p. 362).

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Food security requires both sufficient quantity and quality of food. Nutritious food is needed to prevent hunger and malnutrition for a growing world population, especially when much of that growth is in the elderly (Pedersen and Cederholm, 2014). Animal products are high-quality foods that provide essential amino acids, minerals (e.g., iron and zinc), and vitamins (e.g., B_{12}) that humans need in addition to anti-inflammatory long-chain *n-3* polyunsaturated fatty acids and conjugated linoleic acid (McAfee et al., 2010); thus, a balanced diet contributes to a healthy diet.

Animal products are much more than a source of protein; thus, replacing animal protein with vegetable protein sources eliminates the other nonprotein components of animal products that provide several essential nutrients with greater bioavailability than nonanimal sources (Leroy et al., 2022). Vieux et al. (2022) confirmed that about 45% to 60% of the human requirement for protein must be met by animal protein to meet nonprotein, nutrient-based recommendations at no additional cost. The frenetic and often unsubstantiated association between human disease and animal products (especially red meat) and the perceived environmental burden of ruminant production is harmful and not based on scientific evidence. It may have a long-lasting impact on the population's nutritional status because it divorces the public from a portion of nutritious food that is otherwise a critical component of healthy diets.

Our goals are to 1) discuss relevant aspects of beef cattle production in the U.S. to society and the environment, 2) shed some light on different ways to optimize beef cattle production within a climate-smart-sustainable setting, and 3) mitigate beef cattle production's contribution to climate change. Tedeschi (2022) published a preliminary discussion about this topic.

The beef cattle industry

The beef cattle industry in the U.S. has undergone remarkable changes since Columbus brought a few draft animals to the New World in 1493 (Wilson et al., 1965). Figure 1A shows the evolution of the cattle inventory in the U.S., revealing rapid growth but a more pronounced cyclicity (sinusoidal shape) before the 1960s. The changes in herd size over time are primarily due to beef producers' responses to the difference between costs of production and beef prices, which are mainly driven by consumer demand and beef supply. When consumers are willing to pay a beef price that exceeds production costs, producers are encouraged to increase herd size by retaining more female calves for breeding rather than selling them to be finished for beef. It takes about 3 years before these calves become part of the beef supply. When the beef supply increases, the beef price usually decreases, reducing the national beef herd until the price paid exceeds production costs. The oscillatory behavior of consumer demand and beef supply creates the so-called cattle cycle. Among other things, a widespread reduction in feed supply due to drought or high prices for grain affects the cattle cycle. The cattle population peaked in 1975 with 132 million animals (beef and dairy cows, bulls, calves, heifers, and steers), but since then, it has decreased to a lower plateau, just under 100 million animals (Figure 1A). Similarly, the inventory of beef cows mimics the cattle inventory pattern; it peaked in 1975 at 45.7 million (Figure 1A). In contrast, the inventory of dairy cows peaked in 1945 with 27.8 million animals and has steadily decreased since then (Figure 1A). Others have provided additional characterization and analyses of the dynamics of the beef cattle population in the U.S. and its environmental impacts (Capper, 2011; Rotz et al., 2015, 2019). Despite the reduction of the cattle herd in the U.S., beef production has increased to 37.76 million kg per year since 1975 (Figure 1B), confirming that technological innovations for cattle production have kept up with increased demand for beef due to population growth, but with a smaller cattle herd. Figure 1B shows that during the last 44 years (1975 to 2019), the per capita boneless beef consumption has decreased by over 33% (37.7 to 25.1 kg/yr) (USDA, 2021a).

From 1975 to 2019, the U.S. population increased by over 52% (215.9 to 328.5 million), while the availability of boneless beef increased by only 1.25% (USDA, 2021a). Worldwide, the demand for meat (and milk) is expected to continue rising, especially in developing countries, given the population's increased socioeconomic power and urbanization (Delgado et al., 1999; Mottet et al., 2017). Beef cattle production is the most important agricultural industry in the U.S., consistently accounting for the largest share of total cash receipts for agricultural commodities. In 2021, with 93.6 million animals (Figure 1A), cattle production represented about 17% of the $391 billion in total cash receipts for agricultural commodities (USDA, 2021b). Given the magnitude of cattle entrepreneurship in the U.S. economy, diverging public perceptions and opinions about cattle operations exist. Cattle operations are prone to criticism related to the perceived environmental burden they pose. These perceptions often reflect incomplete information disseminated about the social, economic, nutritional, and ecological benefits or detriments of cattle operations in the U.S.

Greenhouse gas emissions and global warming

Agriculture's ubiquitous and unanimous ability to improve livelihood and food security around the globe is often unappreciated in many discourses about global warming partly because most people are distant from our food system and do not have the correct information to make rational decisions based on facts. Global warming is a real climatic phenomenon (Weart, 2008; Archer and Pierrehumbert, 2011), most likely caused by society's incessant misuse of nonrecycled/nonrenewable natural resources. It is a threat to humankind, and it should be taken seriously. Carbon dioxide is the most abundant greenhouse gas (GHG) in the atmosphere. Its increased atmospheric concentration due to its increased release rate compared to its removal rate has been mathematically shown to be the most probable genesis of global warming since the mid-1960s (Manabe and Wetherald, 1967, 1975). Emissions of GHG are usually expressed in *Système International* (SI) units as Gigaton (Gt = 1,000 Mt), Megaton (Mt = 1,000 kilotons), or Teragram (Tg = 1 Mt) of equivalent CO_2 (CO_2e), with the various gases, compared based on their respective global warming potential (GWP). All values herein are anthropogenic emissions as reported in national and global GHG inventories. Because the UNEP (2021, 2022) reported that the COVID-19 pandemic resulted in a 4.7% reduction in GHG emissions in 2020 compared with 2019 (UNEP, 2020), we adopted the 2019 estimates for our analysis. Global emissions of GHG have increased from about 37.8 Gt in 1990 to 59.1 Gt CO_2e in 2019 (UNEP, 2020). Fossil fuel emissions accounted for 38 of the 59 Gt CO_2e (64.4%) in 2019. As per the Intergovernmental Panel on Climate Change (IPCC),

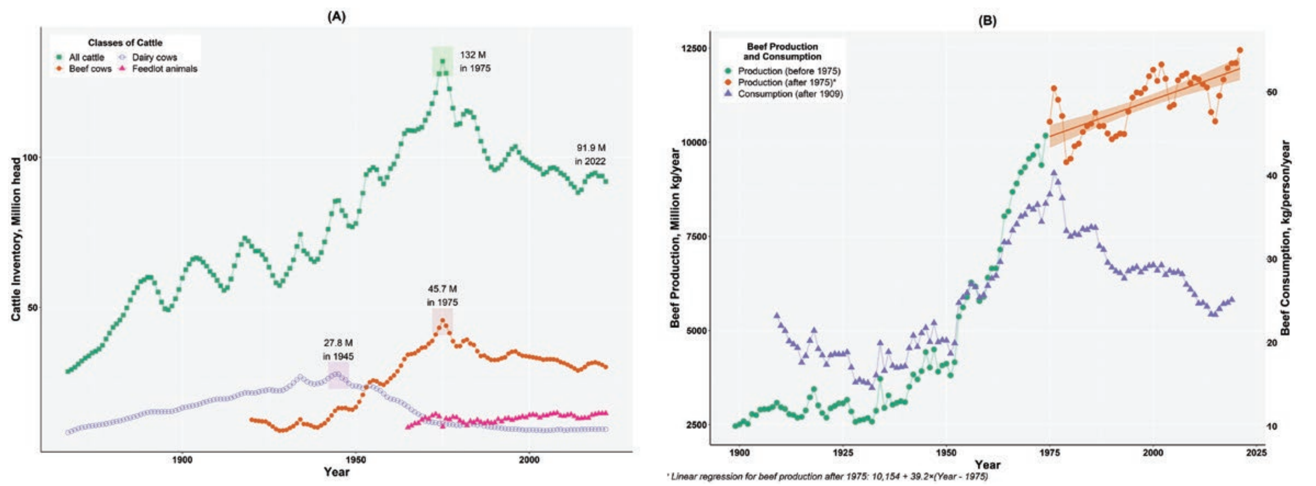

Figure 1. Evolution of (A) cattle inventory and (B) beef production in the United States since 1920 (January surveys). The all-cattle class includes beef and dairy cows, bulls, calves, heifers, and steers. The data sources are https://quickstats.nass.usda.gov (beef production) and https://www.ers.usda.gov (beef consumption). Updated from Tedeschi (2022).

agriculture, forestry, and other land use accounted for about 11% of total GHG emissions (IPCC, 2015), including GHG emissions from deforestation, livestock, soil, and nutrient management (anthropogenic basis). The emissions of GHG have been dropping annually in the last ten years in the U.S. and Japan, but regrettably, not as fast as necessary to achieve climate goals. Data from 2019 indicate that Saudi Arabia, Australia, Canada, the U.S., and China led in terms of GHG emissions per person (21.5×10^3, 20.6×10^3, 19.9×10^3, 17.5×10^3, and 10.1×10^3 kg, respectively) (Leonhardt, 2021).

In 2019, in the U.S., the Environmental Protection Agency (EPA) reported the CO_2e emissions from enteric fermentation (178.6 Mt CO_2e from CH_4, which used a 100-yr GWP of 25) and manure management (82.1 Mt CO_2e from CH_4 and N_2O, which used a 100-yr GWP of 298) was about 3.98% of the total emissions (6,558.3 Mt CO_2e) (EPA, 2021). Note that under the Paris Rulebook, the IPCC (2022) sixth assessment report adopted the 100-yr GWP values of the IPCC (2013; Table 8.7) fifth assessment report of 28 for CH_4 and 265 for N_2O; thus, because the emission metrics are different from those adopted by the EPA, the CO_2e will change. Assuming the EPA emission metrics, when expressed as a proportion of the total agricultural emissions, enteric fermentation was about 28.4%, and manure management was approximately 13.1% (together, they were responsible for 41.5% of the total agricultural emissions) (EPA, 2021). Within enteric fermentation, beef cattle accounted for 72.3% (129.1 Mt CO_2e), and dairy cattle accounted for 24.2% (43.2 Mt CO_2e), whereas within manure management, beef cattle were responsible for 15.6% (12.8 Mt CO_2e) and dairy cattle accounted for 46.4% (38.1 Mt CO_2e) (EPA, 2021). As shown in Figure 2, the EPA (2021) estimated that the 2019 beef cattle herd emitted 22.6% (41.46% × 54.43%) of the total agricultural emissions or about 2.2% of the country's total anthropogenic emissions (9.6% × 41.46% × 54.43%) of CO_2e. These estimates change slightly from year to year (Tedeschi and Fox, 2020a; Dillon et al., 2021), but beef cattle are usually estimated to be responsible for about 20% of the total agricultural emissions or 2% of the total anthropogenic emissions (Tedeschi and Fox, 2020a). During the COVID-19 pandemic, the contribution of beef cattle to the total GHG emissions in 2020 was marginally higher (2.3%) than the 2019 estimates (2.2%) (Figure 2). Therefore, even if ways to mitigate 100% of GHG emissions from beef cattle production are employed, the total emissions will be decreased by only 2.2% annually in the U.S. from the direct contribution (i.e., enteric and manure) of CO_2e by beef cattle. Emissions from the U.S. represent about 11% of the global emissions (6.56 Gt CO_2e ÷ 59.1 Gt CO_2e); thus, the U.S. beef cattle production was responsible for 0.242% of the world's emissions. For comparative purposes, agriculture was responsible for 8.1% of total anthropogenic emissions in Canada, and GHG emissions from enteric fermentation plus manure management of Canadian beef cattle operations were responsible for 37.7% of agricultural activities or 3.1% of total Canadian anthropogenic emissions in 2019 (ECCC, 2021).

Contributions of beef cattle production to global warming

The complexity of beef cattle production systems is formidable and challenging to contemplate, given the intricate interrelationships among players, geolocation of the operations, contrasting ecosystems (landscapes, vegetation, soil, weather, and resources), and economical marketing volatility. Due to the diversity of beef cattle production systems (Ominski et al., 2021), a panacea to solve beef cattle production's environmental impact does not exist, and a one-solution-fits-all scenario to reduce its environmental impact will undoubtedly fail. Although the enteric contribution of the U.S. beef cattle production seems small, if not negligible globally, the indirect contribution of cattle production, including the GHG emitted to produce, fabricate, and commercialize beef products (feed production, animal transportation, and product processing, transportation, and commercialization), adds to the animal's direct contribution. Therefore, beef cattle production (from birth to plate) is an important agricultural activity that needs to reduce its GHG footprint. If sustainable alternatives exist (including any of the three pillars of sustainability: social, environmental, and economic (Tedeschi et al., 2015)) to current beef production practices, producers should be

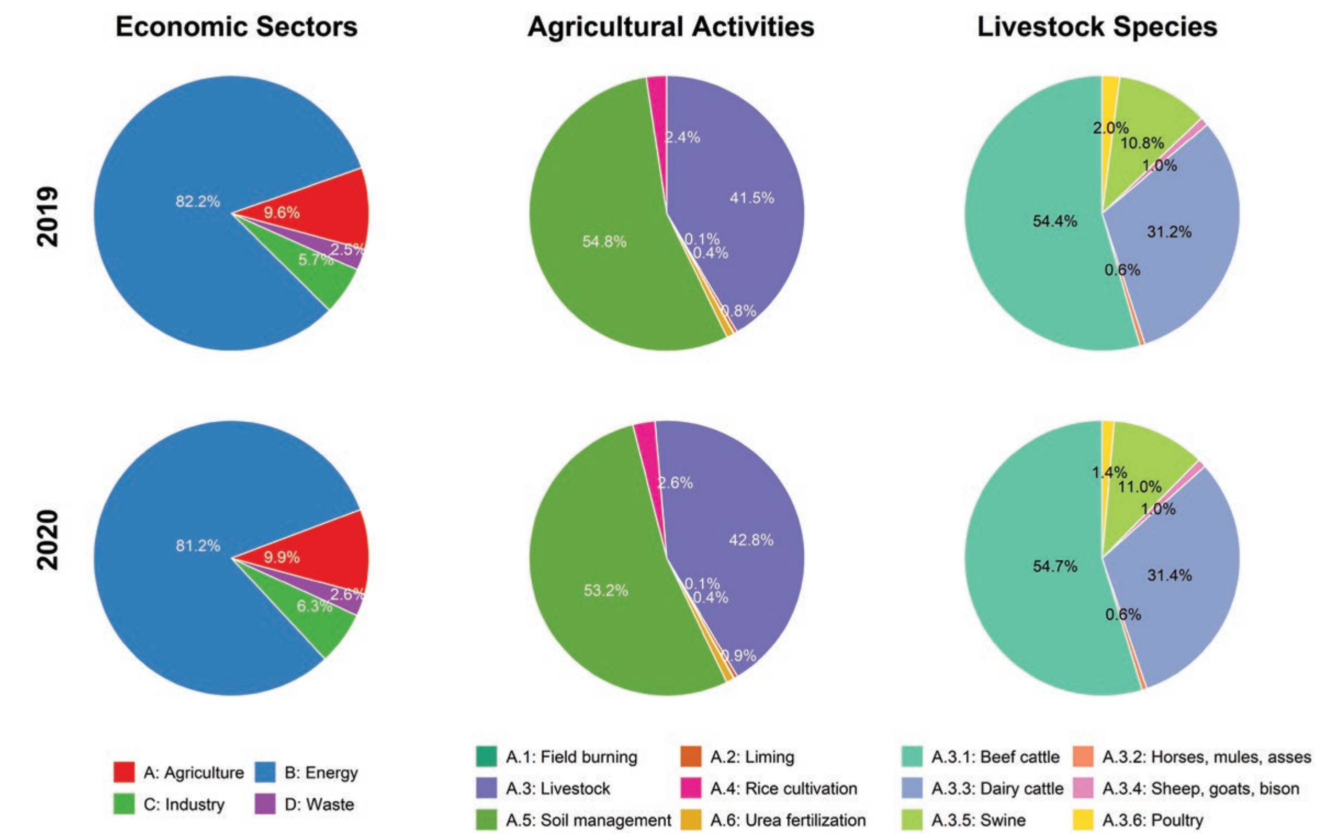

Figure 2. Relative proportions of greenhouse gas emissions (equivalent carbon dioxide, CO_2e, basis) by economic sectors, agricultural activities, and livestock species in the United States. In 2019 and 2020, total anthropogenic emissions by the economic sectors were 6,558.3 and 5,981.5 Mt CO_2e in the U.S. (EPA, 2021, 2022) and 59.1 and 56.3 Gt CO_2e in the world (UNEP, 2020, 2021, 2022), respectively.

encouraged to adopt them. Another, perhaps more appealing, reason to reduce CO_2e footprint is that although rigorous scientific methods are employed, uncertainties in the emission estimates exist (Tedeschi et al., 2022), and when more precise measurements become available, they might swing the contribution of beef cattle (and other livestock activities) upward compared with the status quo.

The Energy-Rapid Overview and Decision Support (En-ROADS) system is a dynamic climate-energy simulation developed by the climate think-tank Climate Interactive and the MIT Sloan Sustainability Initiative (Jones et al., 2021) to address global energy and climate challenges. It has been used by multinational businesses to understand sustainability strategies to meet climate goals (Kapmeier et al., 2021). Figure 3 presents simulations conducted with En-ROADS on the impact of livestock and crop production systems on global warming. Figure 3A has the simulation results for the business-as-usual scenario (i.e., baseline scenario). The estimated GHG emissions for 2019 and 2030 were 57 Gt CO_2e (close to the EPA's 2019 assessment of 59.1 Gt CO_2e (UNEP, 2020)) and 61.55 Gt CO_2e, respectively, which is about a 4% increase from that estimated in 2019 (i.e., 57 Gt CO_2e). The temperature increase was estimated to be 1.53 °C by 2030, consistent with the 1.5 °C maximum set by the Paris Agreement (Fekete et al., 2021; Boehm et al., 2022). When the agricultural and waste emissions of CH_4 and N_2O were assigned a -100% maximum action (https://www.climateinteractive.org/blog/how-to-talk-about-food-in-en-roads/), i.e., using En-ROADS assumptions for extreme improvements in livestock and crop production systems (Figure 3B), En-ROADS estimated 58.67 Gt CO_2e for 2030 (a 4.6% reduction from the business-as-usual prediction, 61.55 Gt CO_2e, Figure 3A), but the temperature increase was estimated to be 1.53 °C for 2030 (same as the business-as-usual scenario in Figure 3A). The findings by Eisen and Brown (2022) that the removal of animal agriculture could reduce 68% of CO_2e emissions contrast with those simulated by En-ROADS. The adoption of extreme improvements in livestock and crop production systems (i.e., reasonable reduction in agricultural CH_4 and N_2O emissions) is considerably greater (nearly twice greater) than the removal of the beef cattle sector contribution only (4.6% vs. 2.2%, respectively), and yet, it had little impact on the temperature increase, suggesting that current extreme measures to decrease GHG by the beef cattle sector may have little effect by 2030 but might decrease the temperature change by 0.2 °C units (3.6 to 3.4 °C, Figure 3) by 2100. Unfortunately, the impact of anthropogenic activities on global ecosystems might go beyond 2100 if GHG emissions continue to rise. Without considering technological innovations in animal production and other agricultural activities, Lyon et al. (2022) recommended that projections should span beyond 2100, given their findings on global climate changes and the effects on human well-being. The question then becomes, at what social and economic price would it make sense to continue down this beef cattle GHG mitigation path in the U.S. and worldwide? Moreover, perhaps, more importantly, will it pay

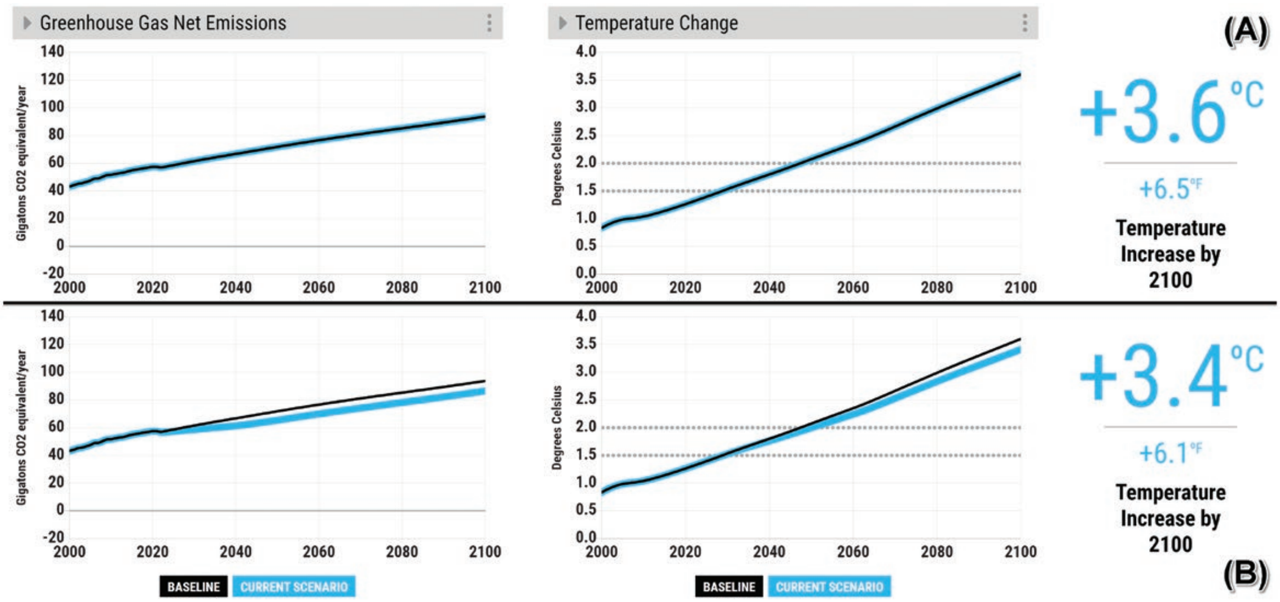

Figure 3. Comparative impact of (A) a business-as-usual scenario and (B) complete removal of agricultural (crop and livestock) and waste emissions of CH_4 and N_2O scenario on greenhouse gas emissions and temperature change. Scenario B was obtained by assigning –100% to the 'Agricultural and waste emissions' in the 'Methane and Other' in the 'Land and Industry Emissions' tab). Simulations were conducted with En-ROADS version 21.9 (https://en-roads.climateinteractive.org/scenario.html?v=21.9.0) (Jones et al., 2021).

off to decrease high-quality meat production from beef cattle to offset 2.2% of CO_2e from that sector in the U.S., or are there other CO_2e sources that should be a much higher priority to mitigate that would have a greater and broader impact, and how do we go about addressing those sources? For example, the main culprit of global warming—burning coal—has been known since 1912 (Molena, 1912), and little has been done to decrease its impact. Other actions to mitigate GHG have been proposed to substantially reduce 'personal emissions' such as having one fewer child, living car-free, avoiding airplane travel, and eating plant-based diets (Wynes and Nicholas, 2017). Needless to say, the provocative 'having one fewer child' action was not well received (Pedersen and Lam, 2018; van Basshuysen and Brandstedt, 2018). Furthermore, although White and Hall (2017) indicated that eating plant-based diets could reduce GHG emissions in the U.S. by 2.6% units, the authors suggested that this eating preference cannot fully satisfy the nutritional needs of humans.

There are many controversial concerns about beef cattle production, and the trend has been to lump these concerns together (Godfray et al., 2018) to label the overall activity as harmful. One must analyze each component under rigorous scientific scrutiny and conclude within the context that they were interpreted. The ideology that current meat consumption needs to decrease by 75% (Hedenus et al., 2014) to prevent Earth's global warming seems extreme, given the limited impact estimated by current computer models (e.g., En-ROADS) and possible nutrient deficits in human diets. Livestock production does much more than simply provide high-quality protein foods to humans (ILRI, 2012). From a big-picture scenario, at the global scale, livestock sustains smallholder livelihood by providing food and increasing human health, assisting with the farming workload, improving dryland use, sequestering carbon (C) into the soil associated with the grasses grown to support ruminants, and serving as models for the development of pharmaceutical compounds for human use, among many other benefits (Cheeke, 2003; Damron, 2013; Tedeschi et al., 2015). Although dependence on livestock production varies widely among countries, its significance is irrefutable: livestock production accounts for between 7% and 31% of kilocalories and between 20% and 60% of protein consumption globally (FAO, 2006). Like any other economic activity, there are positive and negative impacts of beef cattle production, but the balance matters the most, and in the end, the net result might be positive but inconspicuous if one focuses only on GHG emissions.

Livestock production is not immune to the harmful effects of climate change, including impairments in meat and milk yield and quality; egg yield, weight, and quality; reproductive performance; health status (welfare); and immune response (Nardone et al., 2010). Thornton et al. (2021) believe the pervasive impact of extreme heat stress will inevitably affect the viability of outdoor livestock production, especially in the tropics and sub-tropics. Small ruminant researchers have actively selected breeds to be more thermally resistant (Leite et al., 2021), whereas fewer experiments have assessed the impact of warming on the performance of large ruminants, although many indigenous breeds show tolerance to heat and drought (Tedeschi et al., 2017a, 2017b).

Methane Emissions

As enteric CH_4 is the greatest contributor to the CO_2e emissions from beef cattle production, we explore the potential for measurement and mitigation in greater detail below.

Methodological limitations

There are two approaches used to assess CH_4 emissions. The first one is the *bottom-up* approach. Bottom-up approaches sum up the estimates of identified single sources (e.g., livestock, manure storage facilities, gas pipelines) to estimate global emissions. Many methods and techniques are used to determine enteric CH_4 emissions from ruminant animals, including gas exchange measurements such as respiration chambers, head or face masks, and spot sampling (e.g., sniffers); tracer gasses such as sulfur hexafluoride (SF_6); and laser technologies (Lassey, 2007; Storm et al., 2012; Hammond et al., 2016; Jonker et al., 2016). These methodologies are designed mainly for research rather than commercial farms, each having strengths and weaknesses (Hammond et al., 2016; Jonker and Waghorn, 2020a, 2020b), and therefore, the data cannot be compared directly. Despite the availability of techniques to measure CH_4 emissions (Lassey, 2007), most measurements are limited to a few animals (i.e., may not be representative of the entire herd), controlled intake (i.e., may not account for fluctuations of intake), known diet characteristics, and specific requirements (e.g., sniffer method accuracy decreased when the distance of the muzzle was greater than 30 cm (Huhtanen et al., 2015)) that do not occur in practice. A direct comparison of CH_4 emitted by cattle across studies is practically impossible because of intrinsic variations in the methodology and equipment adopted by different research groups (Tedeschi et al., 2022). For example, in an analysis of 397 peer-reviewed studies that used respiration chambers (55%), SF_6 (38%), and headstalls (7%), Della Rosa et al. (2021) reported significant variation that could undermine confidence and data quality. Lack of standardization included measurement duration from 1 to 8 days in respiration chambers, and only 32% of the studies reported gas recovery (ranging from 85% to 107%).

Parallel to field data collection, computer models have been developed to estimate GHG emissions by ruminants (Rotz et al., 2019, 2020; Tedeschi, 2019; Tedeschi and Fox, 2020a, 2020b). The IPCC uses straightforward empirical approaches to assess GHG emissions by ruminants (IPCC, 2019a), but a limitation is that these empirical approaches only work for conditions similar to those in which the equations were developed, and predictions rarely satisfy the statistical requirements, including the existing original (co)variance among variables. Furthermore, some of the assumptions used in these empirical approaches may not hold for all production conditions, such as multiplying the number of animals by a fixed coefficient without considering idiosyncratic characteristics of distinctive types of animals, feedstuffs, and management of CH_4 emissions. Accordingly, Beck et al. (2022) reported significant differences between EPA vs. FAO methodologies to estimate the CO_2e contribution of beef cattle.

Given the inherent limitations of bottom-up approaches, a *top-down* approach is sometimes used. Based on a literature review by the National Academies of Sciences, Engineering, and Medicine (NASEM, 2018), *top-down* approaches estimate emissions using atmospheric CH_4 concentrations (e.g., measured using drones, towers, satellites) and transportation models to assign emissions to sources. There is an assessment disparity between approaches used to estimate CH_4 emissions. Although *top-down* approaches may provide the most accurate estimates of global CH_4 after mass balance is applied to global sources and sinks (Lassey, 2008), questions still exist about their discrepancies (NASEM, 2018). The main concern is how *top-down* approaches assign emissions to known sources considering that unknown sources might exist. For instance, when a source is unknown, the question becomes how its share is allocated to known sources and how reliable the transport models are (NASEM, 2018). The problem is not only to identify unknown sources but also to determine how long it has been emitting unaccounted CH_4. A top-down approach at a farm or regional level does not differentiate between enteric and manure CH_4, whereas a bottom-up approach would measure both sources directly. Furthermore, Froitzheim et al. (2021) report huge uncertainties about the size of C stocks and the magnitude of possible CH_4 emissions from the permafrost given the genesis of CH_4, from either **1**) microbial degradation of the organic matter thawed from the permafrost soils or **2**) the release of trapped natural gas. Another source of CH_4 emissions that is poorly understood is wetlands, leading to significant uncertainty in CH_4 emissions globally (Wilmoth et al., 2021). Because the quantification of CH_4 emissions, especially by ruminants, is complicated by many different factors, and the estimates between bottom-up and top-down approaches rarely agree, the scientific community must improve the techniques and methodology to adequately report CH_4 emission sources and enhance the assessment of GHG inventories (Tedeschi et al., 2022).

Other factors can increase CH_4 emissions under specific climatic conditions. The exposure of *Sphagnum* peat to O_2 can stimulate CH_4 emissions by up to 2000-fold during subsequent anoxic conditions relative to peat not exposed to O_2, likely as a result of changes in the peat microbiome that favor C degradation (Wilmoth et al., 2021). Thus, the volatile CH_4 emission from 1 year to another might be related to the variable exposure of peat to O_2, making peat the second most crucial GHG emitter (Dean et al., 2018). Recent findings suggest that fossil fuels may not have been the first anthropogenic activity to release massive amounts of CO_2 into the atmosphere, although its contribution to global warming is undeniable. The drainage of peatlands to convert them into arable land releases considerable CO_2 into the atmosphere. Peatlands represent only 3% of the land surface but account for more than 30% of soil C (Qiu et al., 2021), making them the most significant natural terrestrial reservoir for C (Beaulne et al., 2021). Apparently, CO_2 emissions can be reversed if the drainage stops and the land rewet (Tanneberger et al., 2021). Similarly, another known source of CH_4 emissions that has been consistently underestimated is water reservoirs (i.e., dams). Harrison et al. (2021) indicated that the emission of GHG from reservoirs is 29% greater than previously suggested on a per-area basis, given current underpredictions of CH_4 ebullition and degassing. It is unclear how the CH_4 emissions are assigned to specific sources when the top-down approaches are used. Perhaps, we need to answer the following question: how and which source receives the real CH_4 contribution from reservoirs and peatlands when using top-down approaches if mistakes in their estimated emissions exist?

Mitigation opportunities

Significant potential exists to mitigate GHG emissions from ruminant livestock production systems worldwide. GHG mitigation can be achieved through many different approaches, including intensifying animal production, implementing enteric CH_4 mitigation practices, improving pastures, changing land-use practices, improving manure management, using renewable fuels, and increasing production efficiency (Thornton and Herrero, 2010; Gerber et al., 2013; Hristov et al., 2013). Among these strategies, intensification of animal production is especially effective for systems with low productivity, such as those in parts of South Asia, Latin America, and Africa, where the C footprint of animal products is very high because farms have low productivity and animals are kept for reasons other than for food production, such as religious, household income, draft, and crop fertilization. Intensification of production to increase meat and milk production improves the efficiency of resource use and decreases GHG intensity (i.e., CO_2e emitted per kilogram of product).

While intensification of animal production is promoted as a highly effective strategy for reducing GHG emissions in developing countries (Thornton and Herrero, 2010; Arndt et al., 2022), its importance for high-income countries cannot be overlooked. For example, a study of beef production in the U.S. showed that compared with 1977, 30% fewer animals were needed in 2007 to produce an equivalent amount of meat, resulting in 18% less CH_4 and 12% less N_2O (Capper, 2011). Consequently, the C footprint of beef produced in 2007 was 84% of the equivalent beef production in 1977. Similarly, a historical examination of dairy production in the U.S. revealed that in 2007, compared with 1944, 79% fewer animals were needed to produce an equivalent amount of milk, and consequently, waste outputs were similarly reduced, with modern dairy systems producing 24% of the manure, 43% of the CH_4, and 56% of the N_2O per kg of milk compared to historical dairying (Capper et al., 2009). Thus, the C footprint of milk produced in 2007 was 37% of the equivalent milk production in 1944. Over time, these decreases in the GHG emitted per kilogram of beef and dairy products (i.e., GHG intensity) were attributed to improved production efficiency, such as better genetics, nutrition, reproduction, health, crop yields, and management.

Increasing animal productivity decreases GHG emission intensity because fewer animals are needed to produce the same amount of product. However, absolute emissions from livestock production only decrease if animal numbers decrease, which has been the trend in the U.S. as previously discussed, but not globally, because animal agriculture continues to expand to meet the demand for food security as the global population increases. In addition to increasing production efficiency to lower GHG intensity, there is an urgent need for mitigation practices that reduce absolute GHG emissions from ruminant livestock production. Globally, the FAO estimated that livestock production contributed 7.1 Gt CO_2e per year (14.5% of global anthropogenic GHG emissions), with 45% from feed production (including land use changes such as deforestation), 39% from enteric fermentation, 10% from manure storage and processing, with the remainder attributed to processing and transportation of animal products (Gerber et al., 2013). For beef production in the U.S., farm emissions are dominated by enteric CH_4 (55 to 60%), followed by emissions from manure (20% to 30%) deposited directly onto pastures for grazing animals (mainly beef cow–calf pairs) and stockpiled in the case of confinement operations [mainly feedlots (Rotz et al., 2019)]. Feed production emissions vary depending on the beef production system but are typically less than the global average because deforestation is not a factor.

The significant contribution of CH_4 to farm GHG emissions, particularly for beef systems, is attributed to the extensive use of roughage-based diets, including preserved forages, grazed pastures and native grasslands, and high-fiber byproduct feeds. In a birth-to-death, life-cycle assessment (LCA) analysis of conventional beef cattle production systems in North America, Beauchemin et al. (2010) reported that roughage feeds make up approx. 80% of the feed resources consumed. While roughage-based diets exploit the evolutionary characteristic and ecological niche of ruminants to use nongrain feeds (i.e., cereals), the fibrous nature of the feed contributes to relatively high-enteric CH_4 emissions. The trade-offs are that beef cattle production does not necessarily compete with people for human-edible foods, and adequately managed grasslands and forage-based cropping systems preserve and augment soil C, reduce the use of N fertilizers, and promote soil health (Guyader et al., 2016). However, most GHG intensities of ruminant products do not typically include changes in soil C stocks and other ecosystem services that pasturelands provide.

Overall, mitigating GHG emissions from ruminant production systems requires a multifaceted approach to tackle emissions from all aspects of the farming system. However, mitigating enteric CH_4 can significantly reduce GHG emissions from ruminant livestock production. Enteric CH_4 emissions in ruminants occur during the process of anaerobic feed fermentation. About 87% to 89% of enteric CH_4 is produced in the rumen and released via eructation, whereas 11% to 13% is produced in the lower digestive tract (Murray et al., 1976, 1978). Most of the CH_4 produced in the hindgut is recirculated through the body and released via the breath, and thus flatulence typically represents less than 4% of the total CH_4 emitted by an animal (Murray et al., 1976, 1978). Presently, there are relatively few commercially available options to reduce enteric CH_4 production, although this is the subject of intense investigation by research groups worldwide (Beauchemin et al., 2020, 2022). Most nutritional interventions seek to suppress or inhibit the ruminal microbes responsible for reducing CO_2 into CH_4 (i.e., methanogenic Archaea), leading to a possible shift in the ruminal microbiome. Nutritional management strategies offer the quickest way to decrease GHG (Hristov et al., 2022). Feeding chemical inhibitors of methanogenesis, such as 3-nitrooxypropanol (3-NOP) or the bromoform-containing red seaweed *Asparagopsis sp.*, are the most effective means of mitigating enteric CH_4 that are currently available or very close to being available (Davison et al., 2020; Beauchemin et al., 2022).

3-Nitrooxypropanol

The feed additive 3-NOP is a chemically synthesized CH_4 inhibitor that inactivates methyl-coenzyme M reductase, the enzyme that catalyzes the last step of methanogenesis in the rumen (Yu et al., 2021). At typical inclusion levels in beef and dairy diets, 3-NOP decreases CH_4 production by approximately 30%, although some feedlot finishing studies have reported reductions of up to 82% (Yu et al., 2021). The effects of 3-NOP are dose- and diet-dependent; CH_4 decreases linearly with increasing 3-NOP concentration in the diet, and the effectiveness of 3-NOP is inversely proportional to the dietary concentration of fiber (Yu et al., 2021), i.e., the greater the fiber the lower the 3-NOP efficacy. The 3-NOP is rapidly hydrolyzed in the rumen to nitrate, nitrite, and 1,3-propanediol (Duin et al., 2016), a carbon source used in gluconeogenesis, and hence 3-NOP is considered to have minimal safety risk or detrimental effects on animals and humans (Thiel et al., 2019). Feeding 3-NOP causes a shift in rumen fermentation from acetate to propionate with no adverse effects on digestibility (Beauchemin et al., 2022). Although enteric CH_4 is a loss of energy (i.e., representing 3% to 10% of gross energy intake), most studies indicate no consistent improvements in animal productivity when feeding 3-NOP. Presently, 3-NOP is approved for use in Brazil, Chile, and the European

Union, but not North America. In its present form, 3-NOP is limited to confinement systems using formulated diets, as it is most effective when included in the diet of animals. However, research is ongoing to develop a slow-release form that might offer the potential for grazing cattle (Yu et al., 2021).

Red seaweed

Two species of red seaweed, *Asparagopsis taxiformis* and *A. armata*, have been shown to decrease CH_4 emissions in dairy and beef cattle production, with efficacy being diet- and dose-dependent (Lean et al., 2021). Reductions in CH_4 yield (kg CH_4/kg of feed) of up to 98% have been reported in beef cattle fed *A. taxiformis* at 2% of organic matter (Kinley et al., 2020). *Asparagopsis* sp. accumulates halogenated compounds (mainly bromoform and di-bromochloromethane), which react with vitamin B12 to reduce the efficiency of the cobamide-dependent methyltransferase step during methanogenesis (Machado et al., 2016). Thus, the efficacy of *Asparagopsis* sp. for CH_4 mitigation depends on its concentration of bromoform (Roque et al., 2019, 2021; Kinley et al., 2020; Stefenoni et al., 2021), which can vary substantially. Effects of *Asparagopsis* sp. on animal performance have been investigated in a limited number of relatively small-scale studies (Li et al., 2018; Roque et al., 2019, 2021; Kinley et al., 2020; Stefenoni et al., 2021). Additional studies with greater numbers of animals and more extended feeding periods are needed to determine the outcome of using *Asparagopsis* sp. for CH_4 mitigation on animal performance under various production systems. Safety issues still need to be addressed, including the potential for bromoform residues in meat and milk. *Asparagopsis* sp. also contains very high levels of iodine, which can accumulate in milk and meat (Stefenoni et al., 2021). In a meta-analysis study using in vitro and in vivo data, Sofyan et al. (2022) indicated that more than 10 g *A. taxiformis* per kilogram of DM might have undesirable levels of bromoform and iodine residuals in milk and that while *A. taxiformis* might decrease CH_4 by about 65% in beef cattle, its efficacy in dairy cows and small ruminants is much less. The GHG emissions from growing, harvesting, processing (drying and extracting), and transporting seaweeds at a large scale will need to be considered holistically; otherwise, its production C footprint might defeat its CH_4 emission mitigation in ruminant production. Despite these limitations, there is tremendous interest in using *Asparagopsis* sp. for CH_4 emission mitigation because it is viewed as natural and is “generally recognized as safe” by some regulatory authorities. There is a compelling need for further research to develop low-cost and environmentally friendly sources and better understand the effects on animal performance, health, and safety of using *Asparagopsis* for CH_4 emission mitigation.

Ionophore antibiotics

The majority of ionophores are produced by *Streptomyces* spp. (Nagaraja, 1995; Tedeschi and Nagaraja, 2020), following the discovery of synthalin used to treat diabetes in humans (Tedeschi and Nagaraja, 2020). The scientific literature is growing, with over 120 ionophore compounds identified (Tedeschi and Nagaraja, 2020). Ionophores are lipophilic ion-bearing molecules that entrench themselves in the lipid bilayer of the bacterial cell membrane, altering its permeability, facilitating the exchange of cations (inflow of K^+ and outflow of H^+), and disrupting cation gradient with a subsequent disproportionate expenditure of energy by the bacteria to expel the intracellular excess of H^+ (Russell and Strobel, 1989). Except in the European Union, ionophores are widely used in beef feedlot diets and dairy production. They consistently increased animals' growth rate and milk yield (Tedeschi et al., 2003; Duffield et al., 2008a, 2008b, 2008c, 2012) and reduced CH_4 by approx. 5% to 10% due to a shift in the ruminal microbiome towards gram-negative bacteria that produce succinic and propionic acids (Chen and Wolin, 1979). Although ionophores have been utilized in ruminant production systems since the early 1980s, some countries have limited or prohibited their large-scale use because of increasing concern about antimicrobial resistance. Furthermore, long-term feeding trials conducted in the mid to late 1990s have hinted at inconsistent results of the inhibition persistency of CH_4 emissions (Tedeschi et al., 2003). The potential for using ionophores for CH_4 mitigation in North America is low because they are already extensively used, and their effects are already reflected in current GHG inventories.

Phytochemicals

Hydrolyzable and condensed tannins in terrestrial plants (Tedeschi et al., 2011, 2014; Spanghero et al., 2022) and phlorotannins present in brown algae (Kim et al., 2022) have been shown to exert anti-methanogenic effects by directly inhibiting some methanogens and indirectly by decreasing protozoal numbers, which symbiotically host methanogens and have a direct relationship with CH_4 production. However, some of the decreases in CH_4 may also be due to a decline in dry matter intake and nutrient digestibility, which can negatively impact animal production (Jayanegara et al., 2012; Arndt et al., 2022). Most tannin-containing legumes grown in the U.S. contain relatively low concentrations (<30 g/kg DM) of condensed tannins; thus, CH_4 reductions are relatively small (<10%). Tannin extracts from shrubs and trees (e.g., *Acacia mearnsii,* chestnut, quebracho) offer an alternative means of incorporating tannins into total mixed rations, but further research is required to determine effective sources and doses (Beauchemin et al., 2022), mainly because the bioactivity of condensed tannins is not fully understood and the results of in vitro and in vivo trials do not correlate satisfactorily (Tedeschi et al., 2021). Saponins are nonvolatile, low-molecular weight compounds of a diverse makeup that makes it difficult to pinpoint their role in controlling CH_4 emission in ruminants. Experimental results have been inconsistent likely because of the transient effect of saponin-containing plant extract from *Quillaja saponaria* (soapbark tree), *Yucca schidigera*, *Sapindus saponaria* (soapberry), *Sapindus rarak*, and *Camellia sinensis* on CH_4 and ammonia production in the rumen (Tedeschi and Nagaraja, 2020). Essential oils are complex, multi-component mixtures of volatile and nonvolatile compounds (e.g., acids, acetones, alcohols, aldehydes, esters, phenolics, and terpenes) with a lipophilic characteristic that might behave like ionophores in the rumen (Tedeschi et al., 2021). The trend has been to develop cocktails of different essential oils as possible replacements for ionophores, but so far, inconclusive results (acetate-to-propionate ratio, fiber digestibility, volatile fatty acid production, mode of action) have dominated the outcome of, mainly, in vitro studies due to the lack of repeatability (Tedeschi and Nagaraja, 2020; Tedeschi et al., 2021).

Diet supplements

The most well-researched dietary mitigation approach is supplementation with non-rumen-protected lipids (e.g., fats, oils, and oilseeds). Various meta-analyses indicate a decrease in CH_4 yield between 3.5% and 5% per 10 g/kg DM supplemental fat, with a maximum supplementation rate of 6% added lipid (DM basis) (Beauchemin et al., 2022). However, widespread use of lipids for CH_4 mitigation is constrained by cost, potential adverse effects on feed intake and fiber digestibility (Arndt et al., 2022; Hristov et al., 2022), and undesirable changes in the fatty acid composition of milk and meat. Similarly, supplementing diets with nitrate (1.5% to 2% of DM) has been shown to reduce enteric CH_4 by 15% to 20% (Arndt et al., 2022; Beauchemin et al., 2022; Hristov et al., 2022). Nitrate draws electrons away from methanogenesis by incorporating them into alternative metabolic pathways. However, nitrite can be absorbed through the rumen wall and react with hemoglobin to form methemoglobin, which cannot transport oxygen. This condition can be fatal, although it is possible to gradually adapt the rumen to nitrate supplementation. Therefore, nitrate use is limited to production systems where the feed intake of individual animals is closely managed.

Diet formulation

In addition to dietary supplements and additives, increasing the concentrate proportion of the diet decreases fiber intake, increases propionate production, increases rumen outflow rate, and lowers rumen pH—factors that decrease CH_4 production (Arndt et al., 2022). However, the decrease in enteric CH_4 production may be offset by increased N_2O and fossil CO_2 emissions due to the use of nitrogen fertilizers for grain production, and soil C is lost during the conversion of pastureland to cropland. Forage management, including increased digestibility, legume use, high-starch forages, and grazing management, can increase dry matter intake and animal performance, decreasing CH_4 yield and intensity (Arndt et al., 2022; Beauchemin et al., 2022).

Other opportunities

Various other nutrition, genetic, microbial, and management strategies to mitigate CH_4 are currently under development and hold promise for the future (Beauchemin et al., 2022). There is considerable interest in the genetic selection of low-CH_4-producing animals as genetic progress is permanent and cumulative over generations. However, determining the CH_4 phenotype of a large number of animals remains exceptionally challenging for dairy and beef cattle breeders (de Haas et al., 2011; Manzanilla-Pech et al., 2021). In addition, selection for low CH_4 emissions may go against economically important traits in beef cattle because there is a positive phenotypical and genetical association between CH_4 production and profitability characteristics, such as feed intake and body weight, and carcass composition traits, such as ribeye area and intramuscular fat (marbling) (Lakamp et al., 2022). Thus, reducing CH_4 production may reduce animal performance (growth and carcass composition), significantly decreasing profit. Simioni et al. (2022) reported an exciting interaction between supplementing or not supplementing a corn diet during the rainy season and three crossbreeding programs (Nellore purebred, Angus × Nellore, and Senepol × Nellore). The Senepol × Nellore cross had greater carcass gain when supplemented with corn, and emitted less CH_4 per carcass gain than the other breeds (Simioni et al., 2022), suggesting that different cattle breeds may respond differently to supplementation (and likely to feed additives) with a reduction of CH_4 emission per animal product. Developing an anti-methanogenic vaccine that stimulates the immune system of animals to produce antibodies against methanogens (Wright et al., 2004) would be highly desirable, but so far, has proven to be challenging (Baca-González et al., 2020) and sometimes vaccinated animals have increased the CH_4 emission likely because of unintended strain selectivity in the rumen (Tedeschi et al., 2011).

Limitations and opportunities

While research provides mitigation options to livestock producers, many challenges limit farm adoption. Much CH_4 mitigation research focuses on confined animals, and few mitigation options are easily applied in grazing systems, which is a significant constraint. CH_4 mitigation is particularly challenging for extensive pasture-based systems because it is difficult to provide feed additives and supplements at the required dose at the individual animal level, yet the beef cow–calf sector is the largest source of enteric CH_4 in North America (Rotz et al., 2019). Another significant barrier is the economics of mitigation, given the lack of improvement in animal production associated with most CH_4 mitigation technologies. Furthermore, the complex and costly regulatory approval process for CH_4-inhibiting feed additives limits their availability in North America.

There is a need to conduct long-term feeding studies to determine the effects of CH_4 reduction on animal health and productivity to determine an optimum CH_4 mitigation level. Despite uncertainties due to methodological discrepancies and without decreasing the current herd size, management and nutritional strategies can reduce CH_4 emissions by, on average, 18%, ranging from 5% to 43% (Arndt et al., 2022). However, a limitation of current meta-analytical studies is that such strategies may overlap in mitigating CH_4 emissions. More combinatorial studies must be conducted to assess the mitigatory overlap effect, and until then, the possible mitigatory effects of stacking up the results of different strategies from different studies might be overestimated and, in some cases, excessive. Gurian-Sherman (2011) proposed that at least 15% to 30% of CH_4 emission reduction could be achieved if improved pasture management practices were adopted for those using continuous grazing practices with beef cattle. However, the mitigatory effects might be situation-specific and do not apply to all production conditions. Thornton and Herrero (2010) reported a more conservative mitigatory impact of only 7% if improved pastures, intensified ruminant diets, changes in land-use practices, and changing breeds of large ruminants were adopted. In the best-case scenario, CH_4 emission mitigation could be up to 43% (Arndt et al., 2022), but it is likely to at least reside between 5% and 15% in practice until more effective strategies (e.g., CH_4 inhibitors and seaweed) become widely available to farmers. The limited extent of CH_4 reduction expected with currently available technologies raises the question of whether the short-term emphasis should be on improving the resilience, rather than sustainability, of the beef production system, given that the intent is to achieve a lower GHG emission rate (to avoid global warming) but with the same output level, including animal products.

Resilient vs. sustainable systems

Any sustainable activity must include a balance among the three pillars of sustainability: social, environmental, and economic (Tedeschi et al., 2015) to achieve the status of sustainability. Historical global trends indicate that social shortfall and economic overshoot prevent sustainability (Fang, 2022) because eight out of 10 social indicators and five out of six ecological indicators needed to meet sustainability have been (1992–2015) or will likely be (2016–2050) violated by most countries (Fanning et al., 2022). Nonetheless, a distinction between resilience and sustainability is needed for better planning when considering future developments. After a perturbation event, resilient systems tend to return to their original output level, whereas sustainable systems tend to stay indefinitely at the new output level (Tedeschi et al., 2015). In this context, resilient systems may need assistance from players outside the system (i.e., exogenous agents), whereas sustainable systems may achieve their balance with internal players (i.e., endogenous agents). Resilient agricultural systems may need intervention from government and policymakers, whereas sustainable systems may not. Sustainable systems depend on the behavior/activity of the individual, internal players of the system, and each small contribution adds up to sustainable behavior. In the context of the beef industry, it is essential to highlight achievements that could lead to sustainable growth and point out success and failures within the system that might contribute to sustainable behavior based on the definitions discussed above.

Human Health And Nutritional Aspects

The increased disease risk of overconsuming animal products (i.e., especially red meat) must not be conflated with the environmental effects of livestock production. Clark et al. (2019) concluded that decreasing the disease risk of one health issue also decreases the disease risk of other health issues, and similarly, foods with a lower environmental burden for one attribute tend to lower the environmental burden of other attributes. They concluded that because "foods associated with the largest negative environmental impacts—unprocessed and processed red meat—are consistently associated with the largest increases in disease risk," choosing healthier food would likely decrease the environmental burden. However, such a broad assertion is complicated because many other factors must be considered, and a wide-ranging generalization like this is misleading. Food choices can negatively affect human health, but meat consumption recommendations by health professionals should be independent of the environmental burden of animal production because the environmental impact is highly variable depending upon location, production system, management, and other factors. For instance, the land area used by beef cattle is typically not suitable for row crops or horticultural produce as most beef cattle in the U.S. are raised on pasture and grasslands unsuitable for cultivation. The lower environmental burden of "healthier foods" depends on the C footprint for transportation, processing, retailing, and food preparation (Heller and Keoleian, 2015), especially for those foods flown into the U.S. Although GHG emissions to produce fruits and vegetables are lower than for nutrient-dense animal products (i.e., beef, milk) on a weight basis, their GHG emission on an energy basis is much greater (Vieux et al., 2013; Drewnowski et al., 2015). However, when GHG emissions are expressed on a protein basis, beef has the highest emission intensity (amount of GHGs emitted per unit of protein), averaging 300 kg CO_2e/kg of protein, with ecosystems, management practices, and supply chain management mainly explaining the variation observed across different production conditions (Gerber et al., 2015).

Different interpretations of the data have led to divergent recommendations about consuming unprocessed red meat and processed meat (Bouvard et al., 2015; Johnston et al., 2019). Bouvard et al. (2015) indicated an association between highly processed meat consumption and colorectal cancer in 12 of 18 cohort studies but ruled out the carcinogenicity effect of the consumption of unprocessed red meat because of limited evidence and inconclusive research data. In contrast, other studies concluded that the consumption of red meat had no association with a higher incidence of coronary heart disease and *diabetes mellitus* (Micha et al., 2010). Some studies have concluded that the consumption of red meat causes many different types of diseases (e.g., type 2 diabetes, various cancers) that could lead to reduced lifespan (Murray et al., 2020), while other studies do not support these inferences (Kappeler et al., 2013). Harcombe et al. (2015) and Johnston et al. (2019) indicated that linking the consumption of animal products to human diseases is often based on insufficient evidence because the associations are frequently drawn from analyzing data collected in observational studies with a high risk of confounding factors that might limit the establishment of causational relationships.

For instance, failure to assess multicollinearity among human diseases (e.g., people who consume high levels of red meat also consume high levels of sugar) will likely provide biased conclusions. Another factor is that the average population lifespan has increased from 71 years in 1970 to 79 years in 2021 (Xu et al., 2019), so presumably, cardiometabolic disease probability also has increased. In 2019, the 75- to 84-year-old group was 2.5 times more likely to contract (and die of) heart disease than the 65- to 74-year-old group (Xu et al., 2019), and yet, the overall per capita consumption of beef has decreased since the 1970s (Figure 1B) (USDA, 2021a). There is a need to assess illness for individuals who do not consume in excess. There is weak and insufficient evidence that the consumption of unprocessed red meat increases colorectal cancer, breast cancer, type 2 diabetes, and ischemic heart disease and has no relationship at all with the incidence of ischemic stroke or hemorrhagic stroke (Lescinsky et al., 2022) when using a relatively novel five-star burden of proof methodology (Zheng et al., 2022). The same methodology, however, pointed out that the consumption of vegetables significantly protected against ischemic stroke, ischemic heart disease, hemorrhagic stroke, and esophageal cancer (Stanaway et al., 2022). The reasons for outcome discrepancies among studies are not entirely clear, but it certainly causes confusion that increases public distrust and undermines health recommendations.

Poor-diet quality and overconsumption of calories are the triggers for diet-related chronic diseases, and the perception that shifting dietary patterns towards plant-based diets could alleviate health and environmental burdens are topics of interest (Hemler and Hu, 2019) but frequently oversimplified and manipulated to reap public appeal. Few studies have looked into health issues among different dietary groups, such as the nutritional value of alternative (i.e., cultured) meats (Van Eenennaam and Werth, 2021) or the relative consumption of synthetic pesticides, given that some pesticides used to grow crops are carcinogenic or tumor promoters (Dich et al., 1997; Bassil et al., 2007). Unfortunately, there is evidence that vegetarian eaters are more prone to ingest significant quantities and different types of pesticide residues than omnivorous eaters (Van Audenhaege et al., 2009). Thus, ruling in favor or against a group of food (red meat vs. plant protein) is not inconsequential; it requires a more profound understanding of variables that might be unknown at this time or omitted when making sweeping dietary recommendations. In reality, the high consumption of calories might be a more critical factor in the prevalence of diet-related chronic diseases than the type of diet per se. Nutritionally balanced diets include small meal portions of diverse foods (e.g., food pyramid). The considerations made by Mariotti (2019) about the "issues when interpreting current and future diet quality in terms of the plant compared with animal protein patterns" is of interest because "it remains unclear whether the association between plant protein intake and overall nutrient adequacy can be ascribed mainly to the intrinsic characteristics of the foods that are currently available to compose our diet (i.e., to the 'protein package' of the usual protein food groups), or if this might be largely confounded by the healthy behaviors of individuals who purposely adopt a diet containing more plants (i.e., linked to overarching factors of diet quality)."

Seeking for a Brighter Perspective for a Long-Lasting Solution

As noted previously, the emphasis on the impact of beef cattle production on GHG emissions over-states its actual contribution to climate change and should not be factored into nutritional recommendations for human health. Finding solutions to global warming that will significantly decrease GHG requires accurate information about the sources and a broader scope, perhaps even changing our viewpoint on the problem. The Earth's biosphere is responsible for most (if not all) feedback loops that control biological cycles, including C; thus, the development of biosphere stewardship (Rockström et al., 2021) that is inclusive to all sectors and actors in the society is required to foster enhanced management practices that conserve, restore, improve, or sustainably manage ecosystem services. Indeed, some beef cattle production systems might be part of the solution to mitigate the C accumulation in the atmosphere through its incorporation in soil. Soil management accounts for 54.82% of total agricultural emissions of CO_2e (Figure 2), which is more than livestock (41.46%). However, it should be noted that the soil management category includes **1**) application of managed livestock manure and **2**) manure deposition on soils by domesticated animals in pastures, ranges, and paddocks (EPA, 2021), sources that are clearly related to livestock production. However, in the absence of livestock manure, greater use of inorganic N-based fertilizers would be required, and hence, cropping emissions would not significantly decline.

Achieving a more enlightened understanding will require collaboration from all fields of science. Soil can be critical in solving the climate change crisis because of the potential for C sequestration from the atmosphere. Soil acts as a reservoir of C. Thus, the impact of soil C on climate change can be positive or negative depending on the competition between the rates of sequestration and release. However, C sequestration in soil depends on many factors that promote the plant's growth and C storage in a more stable form with a slower release rate (i.e., it takes longer to be released into the atmosphere). The potential for soil C sequestration has often been ignored by LCA (Nijdam et al., 2012); thus, guidelines have been developed to assist with the determination of soil C sequestration for beef cattle production (FAO, 2019). In addition to weather-related (light, temperature, water) and soil genesis traits, other factors such as the availability of nutrients (e.g., macrominerals and microminerals) are required by the plants for growth and development, with particular attention to N affecting soil C levels. Many microbial activities in the soil need N; thus, most C compounds formed through microbial intervention will contain N. The C–N biogeochemical interrelationships dictate the sequestration of C and N, leading to the formation of more extensive, stable stocks in the soil. The understanding of the behemothic complexity of the interactions among different ecological cycles and associated signals that regulate them require the translation of theoretical concepts and experimental data into mathematical models, but, despite recent model developments, gaps still exist because the advances have been focused on C only, ignoring subsoil organic matter dynamics, and have been derived by small-scale research (Cotrufo et al., 2021).

So, how can livestock assist with incorporating C into a more stable stock in the soil? Grazing ruminants are an essential component of the C cycle. A study of the grassland of Yellowstone National Park reported that the grazing behavior of American Bison stimulated the growth of nutritious grasses by spreading manure that acts as a fertilizer to the landscape (Geremia et al., 2019). Grazing beef cattle can act as a C sink by increasing its sequestration in the soil depending on the grass management strategy (Undersander et al., 2002; Brilli et al., 2017). Long-term practices of burning grasslands that are used in many world regions can decrease soil organic C and N stocks, contributing to GHG, but when associated with rotation between burning and mowing, it might provide sustainable alternatives to grassland management (Abdalla et al., 2021). Stanley et al. (2018) showed that when using a rotational-type grass management system (Voisin, 1959), the 4-yr C sequestration rate was 3.59 Mg C/ha/yr, leading to −6.65 kg CO_2e/kg carcass (a sink of C) when compared to feedlot finished systems (6.12 kg CO_2e/kg carcass). Wang et al. (2015) reported a similar C sequestration rate of 3.53 Mg C/ha/yr for 10 yr when switching from heavy continuous grazing to rotational grazing. However, LCA analyses indicate that extensively farmed beef production yields three to four times more GHG per carcass than intensively raised beef (50 to 640 vs. 20 to 200 kg CO_2e/kg of protein, respectively), although the variation among LCA analyses is considerable (Nijdam et al., 2012).

Grazing beef cattle can be either a source or a sink for GHG emissions, depending on how the land is managed and the amount of additional C that can be stored in the soil. Establishing pastures onto lands that have been depleted in soil C due to annual cropping or overgrazing can augment soil C, whereas pastures that have been well-managed for decades already have large stores of C and are often at or near equilibrium and soil C cannot be further increased (Guyader et al., 2016). Optimum grazing management can enhance the nutritional quality and amount of herbage available to livestock, promoting animal production per area and decreasing GHG intensity (Guyader et al., 2016). However, the effects of animal grazing on the net GHG balance depend on the soil C stores and how the land was previously managed. For example, Beauchemin et al. (2010) reported that when cattle grazed grassland that was newly seeded on previously cropped land, the gain in soil C more than offset all GHG emissions (including enteric CH_4 production). However, when soils were at equilibrium, the beef production system was a net GHG emitter.

The net-zero emission concept

Definitions abound regarding concepts related to solving the global warming crisis. The "net-zero" emission for CO_2, CO_2e, or GHG means the *anthropogenic* emissions of CO_2, CO_2e, or GHG are balanced by their *anthropogenic* removal over a period of time (IPCC, 2019b). Although industry and governments increasingly recognize the net-zero concept, it is far from fully vetted. The net-zero concept is based on physical science, but it has been implemented through social, political, and economic venues without considering equitable net-zero transition and the socio-ecological pillars of sustainability (Fankhauser et al., 2022). However, the net-zero emission concept will not eliminate global warming; it will put global warming on a standby state because, in the first instance, it seeks to balance the CO_2, CO_2e, or GHG anthropogenic emissions with CO_2, CO_2e, or GHG anthropogenic removals, keeping their concentration the same as today (or whenever the "net-zero" emission happens). Computer simulations conducted by Lowe and Bernie (2018) indicate that even under net-zero conditions, global warming will continue increasing because of the inertia of the Earth's system feedbacks, such as ocean temperature and permafrost thawing's C release rate. In reality, the solution for global warming has to be based on a "sub-zero" or "net negative" emission concept to effectively remove the CO_2, CO_2e, or GHG already accumulated in the atmosphere to bring down their concentration and, with it, the global temperature. Therefore, achieving net-zero emissions might not be as straightforward and quick as needed to promote a decrease in the concentration of atmospheric GHG. While it is not expected to decrease climate warming, net zero will help slow the rate of increased climate warming.

Some advocate that there is no new release of C by ruminants because the CH_4 being eructated is part of a C cycle; therefore, ruminants do not contribute to global warming. Within the C cycle, the C is present in different forms (as CH_4 or CO_2 or glucose—$C_6H_{12}O_6$) at a given time, but one C form does not accumulate because it is in dynamic equilibrium, i.e., the net rate to the system is zero. One of the critical steps in the mathematical modeling of complex systems is setting the problem's boundaries (Sterman, 2000; Hannon and Ruth, 2001). The second step is identifying important state and rate variables (i.e., stock, flow) to the problem (Sterman, 2000; Hannon and Ruth, 2001). Another point is the time step needed to simulate the dynamics of the problem. In total, 1 yr is too long for an animal, but it is not for climatic events. In that sense, if the animal sets the boundary of the problem, then food C is an inflow rate, CH_4 is an outflow rate, and C can accumulate in the animal (as it does). But, if the atmosphere establishes the boundary of the problem, animals do not contribute to any C accumulation within the system; it is just being recycled over time, in one form or another. Thus, the C is simply transformed from one form (CO_2) to another (CH_4) to sustain life without adding new C to the atmosphere. The CH_4 produced in the rumen and eructated by ruminants (Tedeschi and Fox, 2020a) joins the CH_4 produced by many other sources in the troposphere, where it is short-lived because 85% of the CH_4 reacts with OH in the presence of sunlight ($CH_4 + OH \rightarrow H_2O + CH_3$) (Cicerone and Oremland, 1988). Eventually, CH_4 is completely oxidized to CO_2 ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$) though this reaction is not as simple as it looks because it requires many intermediate reactions, including the formation of formaldehyde, which is oxidized to CO and then to CO_2 in the presence of NO_x (Cicerone and Oremland, 1988). Plants then sequester this CO_2 (recently converted from CH_4), and through photosynthesis in the presence of sunlight, "energy" in the form of ATP is associated with the CO_2, forming molecules of sugar such as $C_6H_{12}O_6$ (Campbell and Norman, 1998; Reece et al., 2013) that can be further converted to other more complex structures such as cellulose. The remaining 15% to 20% of the CH_4 is transported upward to the stratosphere and destroyed (Cicerone and Oremland, 1988).

Herbivores (second trophic level), including ruminants, consume the carbohydrates synthesized by the plants (first trophic level), extract their energy through metabolic oxidation, and use them in diverse physiological needs for survival. However, in the digestion process of ingested carbohydrates, some CO_2 is reduced to CH_4 to support microbial growth in the rumen during anaerobic fermentation by reducing the coenzyme M (2-mercaptoethane sulfonic acid) (Russell, 2002; Dehority, 2003). This exergonic process serves as the terminal acceptor for the methyl group and allows for ATP synthesis (Russell, 2002; Dehority, 2003)—usually, the reduction of CO_2 to CH_4 by methanogens yields 1 mole of ATP (Thauer et al., 2008). These microbes are beneficial to ruminant animals. They are responsible for degrading cellulose (mammals cannot digest it) and, as a side benefit, they convert different non-protein N sources (e.g., ammonia, urea, and nitrates, which cannot be used by mammals either) into amino acids that the ruminant animal uses as the building block of body proteins. Ruminants eliminate this CH_4 through eructation, as it has served its purpose of reducing CO_2 and fixing excess of H, and the process (i.e., cycle) starts again.

The production of CH_4 by ruminants during the ruminal fermentation process has occurred for millions of years since the Miocene when ruminants are believed to have appeared on Earth (Vrba and Schaller, 2000; Prothero and Foss, 2007). The bottom line is that because no new C is released into the atmosphere by ruminants when their population is relatively stable, livestock production cannot be held responsible for increasing global warming. In the case of the U.S., as shown in Figure 1A, the cattle population has steadily decreased since 1975. In that sense, only taking into account the decrease in the cattle herd from 1975 to 2021, the average CH_4 emissions by the U.S. cattle herd decreased by about 30% (i.e., 381.5 Mt CO_2e/yr in 1975 to 269.3 Mt CO_2e/yr in 2021), as shown in Figure 4. The mechanistic solution of the Ruminant Nutrition System model (Tedeschi and Fox, 2020a, 2020b) was used to estimate the average CH_4 emission. At the same time, the standard deviation was obtained from the predicted average of several empirical equations using typical diets for beef and dairy cattle. Hence, when considering the 95% confidence intervals (Figure 4), the decrease could have been as much as 69%. This deacceleration in CH_4 emission (2.46 Mt CO_2e/yr^2) was computed only assuming herd size when, in reality, animal management and diet quality changes would likely increase the predicted drop in CH_4 emissions by the cattle herd. However, the problem becomes more complicated when we produce feedstuffs to use as feed in concentrated animal operations (e.g., feedlots, dairies), using inorganic fertilizers, tractors and other types of machinery that use petroleum. Fossil fuel combustion is a process that

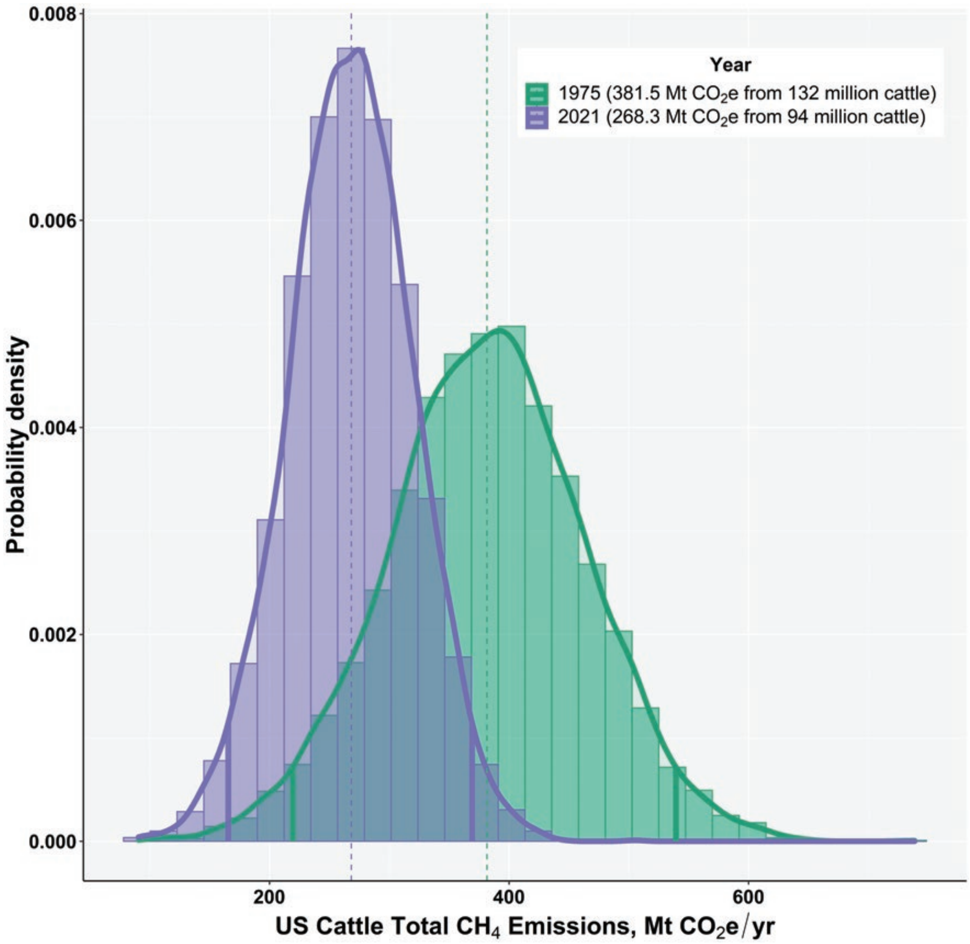

Figure 4. Simulated distribution of total methane production by the cattle herd in 1975 and 2021, assuming average and standard deviation of predicted daily methane production for beef and dairy cows and feedlot animals consuming typical diets. The 95% confidence intervals (vertical segments under the respective density curves) are 219.6 and 539.3 Mt CO_2e/yr for 1975 and 165.6 and 369.2 Mt CO_2e/yr for 2021. Simulations of methane production were conducted with the Ruminant Nutrition System using the mechanistic and empirical levels of solution (Tedeschi and Fox, 2020a, 2020b).

releases previously deposited C into the atmosphere; therefore, a fundamental contributor to global warming. Emissions from feedstuff production are typically assigned to the C footprint of animal production. An important consideration is that if animals did not consume the plants, they could be used for human consumption (at least partially). However, humans cannot consume silage, hay, and crop byproducts due to their high-cellulose content, so the production of biomass per [land] area is higher when used to produce feedstuffs for animals than to produce food for humans. So, is it more sustainable to feed animals and use animal products for human consumption or use the land to produce plants for human consumption? The answer is relatively simple—it is a case-by-case situation; one solution is inadequate.

Conclusions

Beef cattle production contributes a relatively small proportion (less than approx. 3%) of the total anthropogenic emissions of GHG, on a CO_2-equivalent basis, in the U.S.; thus, its elimination would do little to address the climate change problem. Many mitigation strategies might decrease beef cattle's GHG contribution, but the economics of implementation is unknown. In addition, significant reduction or complete removal of red meat from the American diet might result in unintended environmental consequences and worsen human health, given that animal products supply concentrated forms of energy, protein, essential amino acids and fatty acids, minerals, and vitamins. Efficient, resilient, and sustainable beef cattle production strategies need to be prioritized in the U.S. Some measures include dietary and management interventions of ruminant animals to minimize CH_4 emissions, reducing food waste losses by developing and adopting more efficient logistics (e.g., transportation), local production, adapted animal breeds, warm-season forage production, and drought-tolerant plants and animals to list a few. There is no lack of innovative scientific ideas to reduce CH_4 emissions by beef cattle, and producers are willing and ready to employ them sustainably if economic (and social) incentives are available. Furthermore, meat is a staple food in many countries, given its nutritious value in meeting human protein needs. The importance of the beef industry needs to be acknowledged appropriately, given its past, present, and future commitments to food security and the environment.

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Conflict of Interest Statement

The authors declare no financial conflict of interest with the content of this article.

Data Availability

Data are available on the Zenodo data repository (https://doi.org/10.5281/zenodo.5944737).

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