PERSPECTIVE ARTICLE

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A Holistic Perspective of the Societal Relevance of Beef Production and its Impacts on Climate Change

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Cite as:
Tedeschi, LO. (2022). A Holistic Perspective of the Societal Relevance of Beef Production and its Impacts on Climate Change. doi: https://doi.org/10.5281/zenodo.6078225

Abstract

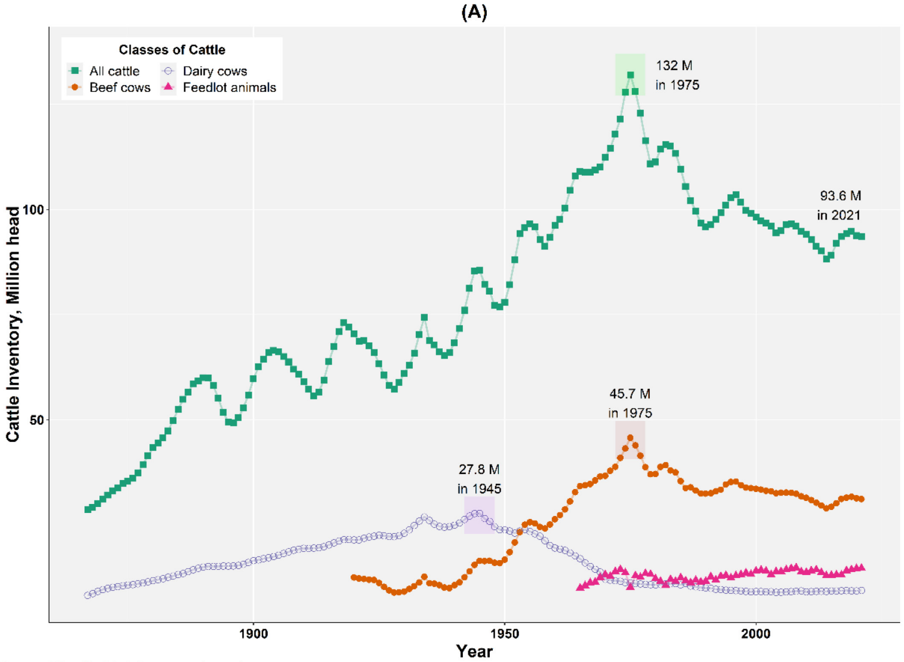
The purpose of this paper is to provide a data-driven realistic perspective on the United States beef herd's relevance to our society and greenhouse gases (**GHG**) contribution to climate change. Cattle operations are prone to criticisms, at times more destructive than constructive, primarily when related to the environmental burden, often reflecting incomplete information disseminated about cattle operations' social, economic, nutritional, and ecological benefits or detriments. The 2019 data published by the US Environmental Protection Agency confirmed that US beef cattle emitted 22.6% of the total agricultural emissions, leading to about 2.2% of the total anthropogenic emissions of 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 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 likely increased contribution of peatlands and water reservoirs to atmospheric CO_2e, the steady decrease of the US cattle population might have reduced its CH_4 emissions, on average, by about 30%, and as much as 69%, when considering only the decrease in the cattle herd from 1975 to 2021. This deacceleration in CH_4 emissions (approx. 2.46 Mt CO_2e/yr^2) by beef cattle might be even more significant because of the beef industry's continuous adoption of improved feeding and management practices since 1975. 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. In addition to region-specific recommendations rather than a global policy, we need a "sub-zero" action to effectively bring down the accumulated atmospheric GHG and, with it, atmospheric temperature.

Keywords: Agriculture, Animal Science, Environment, Greenhouse gas, Production, Resilience, Ruminants, Sustainability.

Introduction

The beef cattle industry

The beef cattle industry in the United States has undergone remarkable changes since Columbus brought a few draft animals to the New World in 1493.[138] Figure 1A shows the evolution of the cattle inventory in the United States, 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 the supply of beef. When consumers are willing to pay a beef price that exceeds production costs, producers are encouraged to increase herd size by retaining more of the female calf crop for breeding rather than selling them to be finished for beef. It will be about three years before their calves become part of the beef supply. When the beef supply increases, 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 essentially mimics the cattle inventory pattern; it also 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). The last cattle cycle started in 2004 with 94.4 million cattle (beef and dairy combined). It expanded to 96.6 million cattle for three years but initiated a decline in 2007 caused by expensive feeds and higher energy costs. The drought conditions of 2011[15] resulted in a further decrease in the beef cattle inventory until it reached a new low in 2014 of 88.2 million cattle (29 million beef cows). These values are similar to those from 1958, at 91.2 million cattle (24.2 million beef cows), just before peaking in 1975. From 2014 to 2019, the cattle inventory has increased to 94.8 million animals but has started declining again. The 2019 inventory (94.8 million) is lower than the previous peak of 97.3 million in 2001 (Figure 1A). Despite the reduction in the cattle herd in the US, beef production has increased at 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, 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/year).[121] However, the US population has increased by over 52% (215.9 to 328.5 million), while the boneless beef availability has increased by only 1.25%.[121] Worldwide, the demand for meat (and milk) is expected to continue rising, especially in developing countries, given the population's increased socio-economic power and urbanization.[21; 83] Beef cattle production is the most important agricultural industry in the US, consistently accounting for the largest share of total cash receipts for agricultural commodities. In 2021, with 93.6 million animals (Figure 1A), cattle production is forecasted to represent about 17% of the $391 billion in total cash receipts for agricultural commodities.[122]



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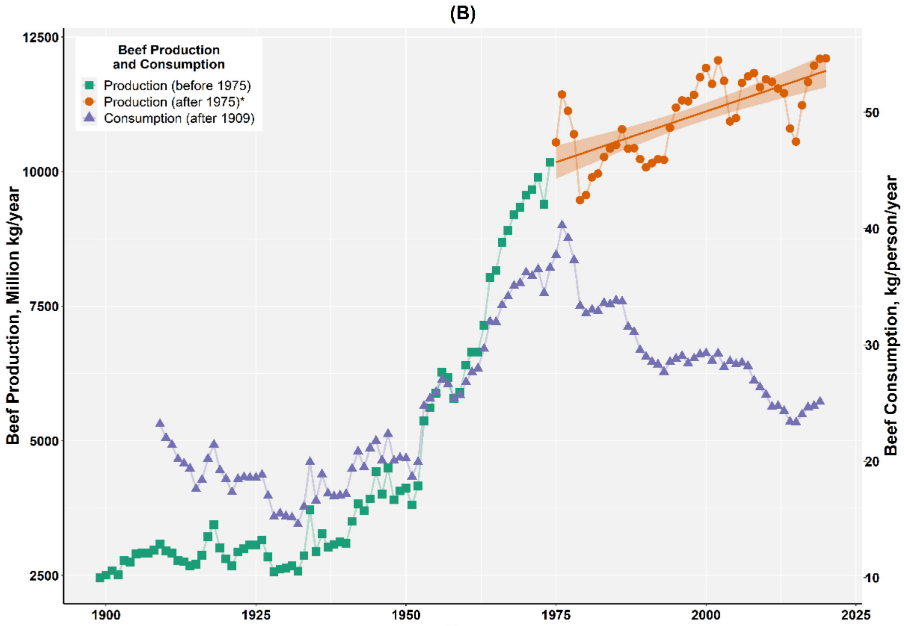


* Linear regression for beef production after 1975: 10,175 + 37.76×Year

Sources: https://quickstats.nass.usda.gov for beef production and https://www.ers.usda.gov for beef consumption

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.

Given the magnitude of cattle entrepreneurship in the US economy, diverging public perceptions and opinions about cattle operations have become routine. Cattle operations are prone to criticisms, at times more destructive than constructive, primarily when related to the perceived environmental burden they might pose. These perceptions reflect incomplete information disseminated about the social, economic, nutritional, and ecological benefits or detriments of cattle operations in the US.

Greenhouse gas emissions and global warming

The United Nations' 2020 report on the planet's health[120] indicates that peril looms over climate talks. This up-and-down situation between sustainable development and climate change has existed since establishing the unattainable goals of the 1997 Kyoto protocol[43] and after many Conference of the Parties (**COP**) meetings about climate change organized by the United Nations. Most negotiations at these conferences have been deemed a "festival of conspiracy and betrayals," given the entanglements generated by politics and hidden agendas.[41] Moreover, up to late-2021, no G20 country has met the goals of the 2015 Paris Agreement,[33] undermining the hopes to limit global warming change by 1.5°C in 2030. The level of excitement and apprehension associated with climate actions always leads to searching for a scapegoat (i.e., something made to bear the blame). Despite agriculture's ubiquitous and unanimous qualities to improve livelihood around the globe, it has been blamed for paving the road to the global warming catastrophe—it has also been paying the bill for quite some time, through slogans like "do not eat this or that because it causes global warming" that abound in different news channels and press media. Unfortunately, many have accepted this pervasive story partly because most people are distant from our food system and do not have the correct information and training to make rational decisions about the facts.

Global warming is a real climatic phenomenon[3; 131] most likely caused by humans' incessant misuse of non-recycled/nonrenewable natural resources. It is a threat to humankind, and it should be taken seriously rather than lightly and sporadically. Some[95] even believe that global warming might have triggered the COVID-19 pandemic. Carbon dioxide and water vapor are greenhouse gases (**GHG**), and their increased atmospheric concentrations due to increased release rates of CO_2 compared to its removal rates have been mathematically shown to be the most probable genesis of global warming since the mid-1960s.[76; 77] Emissions of GHG, usually expressed in *Système International* (SI) units as Gigatons (**Gt** = 1,000 Mt) or Megatons (**Mt** = 1,000 kilotons) or Teragram (**Tg** = 1 Mt) of equivalent CO_2 (**CO_2e**) given their global warming potential (**GWP**), increased from about 37.8 in 1990 to 59.1 Gt CO_2e in 2019.[120] Fossil fuel emissions accounted for 38 of the 59 Gt CO_2e (64.4%) in 2019. Agriculture, forestry, and other land use accounted for about 11% of total GHG emissions[53], including anthropogenic GHG emissions from deforestation, livestock, soil, and nutrient management. The emissions of GHG have been dropping year after year in the last ten years, including in the United States and Japan, but regrettably, not as fast as necessary to achieve climate goals; sadly, data from 2019 indicate that Saudi Arabia, Australia, Canada, the United States, and China led the GHG emission 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).[72]

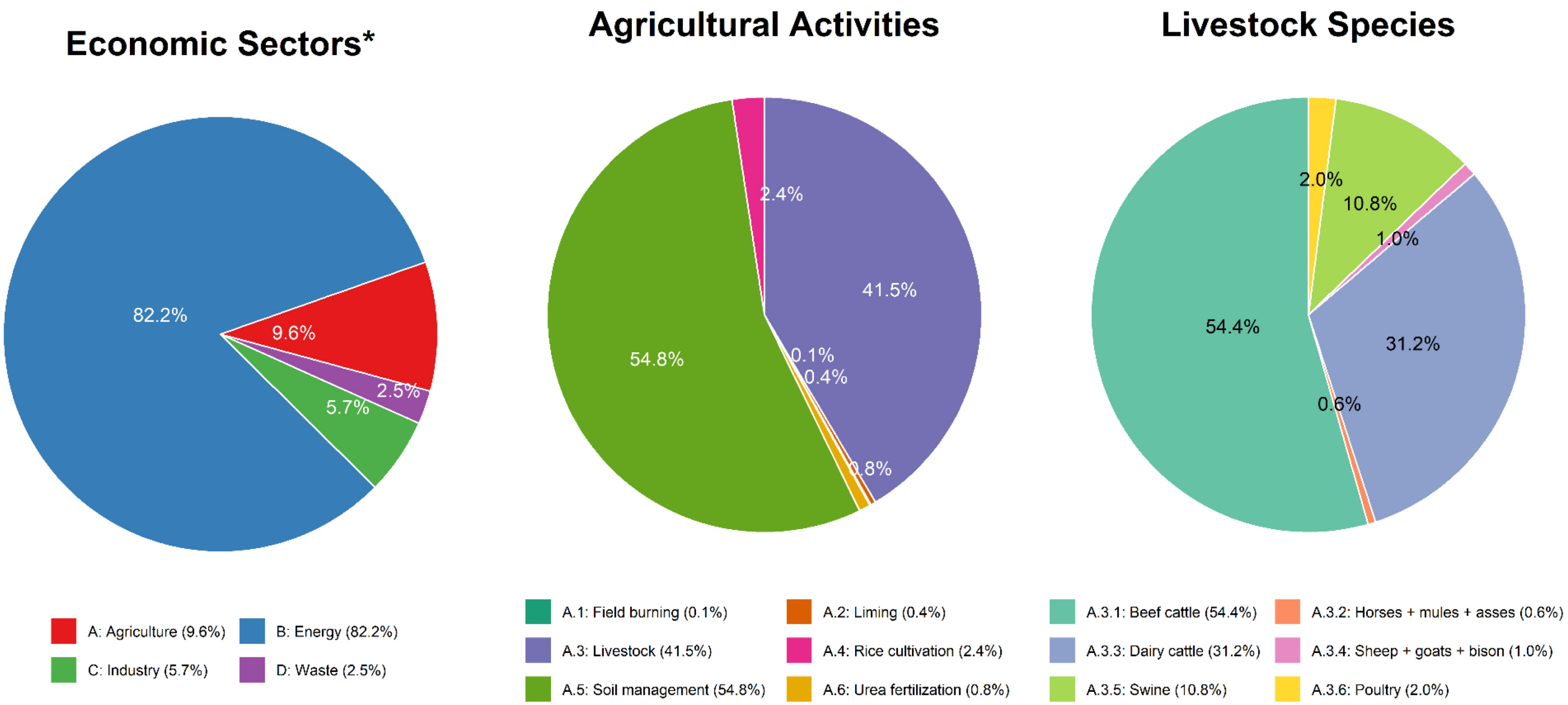
In 2019, in the United States, the CO_2e emissions from enteric fermentation (178.6 Mt CO_2e mostly from CH_4, which has a 100-year GWP of 28) and manure management (82.1 Mt CO_2e from CH_4 and N_2O, which has a 100-year GWP of 265) was about 3.98% of the total emissions (6,558.3 Mt CO_2e).[29] When 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).[29] Within the 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).[29] As shown in Figure 2, the Environmental Protection Agency (**EPA**)[29] 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 total anthropogenic emissions (9.6% × 41.46% × 54.43%) of CO_2e. These estimates change from year to year,[24; 112] but beef cattle are usually estimated to be responsible for about 20% of the total agricultural emissions or 2% of the total anthropogenic emissions.[112] 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 US from the direct contribution (i.e., enteric and manure) of CO_2e by beef cattle. The emissions by the United States represent about 11% of the global emissions (6.56 ÷ 59.1); thus, the US beef cattle production system 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 anthropogenic emissions in 2019.[28]

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, resources), and economic marketing volatility. Like many livestock production systems,[90] a panacea to solve beef cattle production's environmental impact does not exist, and the one-solution-fits-all scenario is doomed to fail. However, although the enteric contribution of the US beef cattle production seems small, if not negligible globally, the indirect contribution of cattle production associated with 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 and might become considerable. Therefore, beef cattle production (from birth to plate) is an important agricultural activity that needs to reduce its GHG footprint. If sustainable alternatives exist (meaning any of the three pillars of sustainability: social, environmental, and economic[116]) to current beef production practices, producers should adopt them to decrease their CO_2e footprint. Another, perhaps more appealing, reason to reduce CO_2e footprint is that although rigorous scientific methods are employed, uncertainties in the emission estimates exist (as discussed next), and they might swing the contribution of beef cattle (and other livestock activities) upwards.

The Energy-Rapid Overview and Decision Support (**En-ROADS**) is a system dynamics climate-energy simulation developed by the climate think-tank Climate Interactive and the MIT Sloan Sustainability Initiative[59] to address global energy and climate challenges. It has been used by multi-national businesses to understand sustainability strategies to meet climate goals.[63] 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[120]) 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



*** In 2019, total anthropogenic emissions by the economic sectors were 6,558.3 Mt CO_2e in the United States (EPA, 2021) and 59.1 Gt CO_2e in the world (United Nations, 2020).**

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.

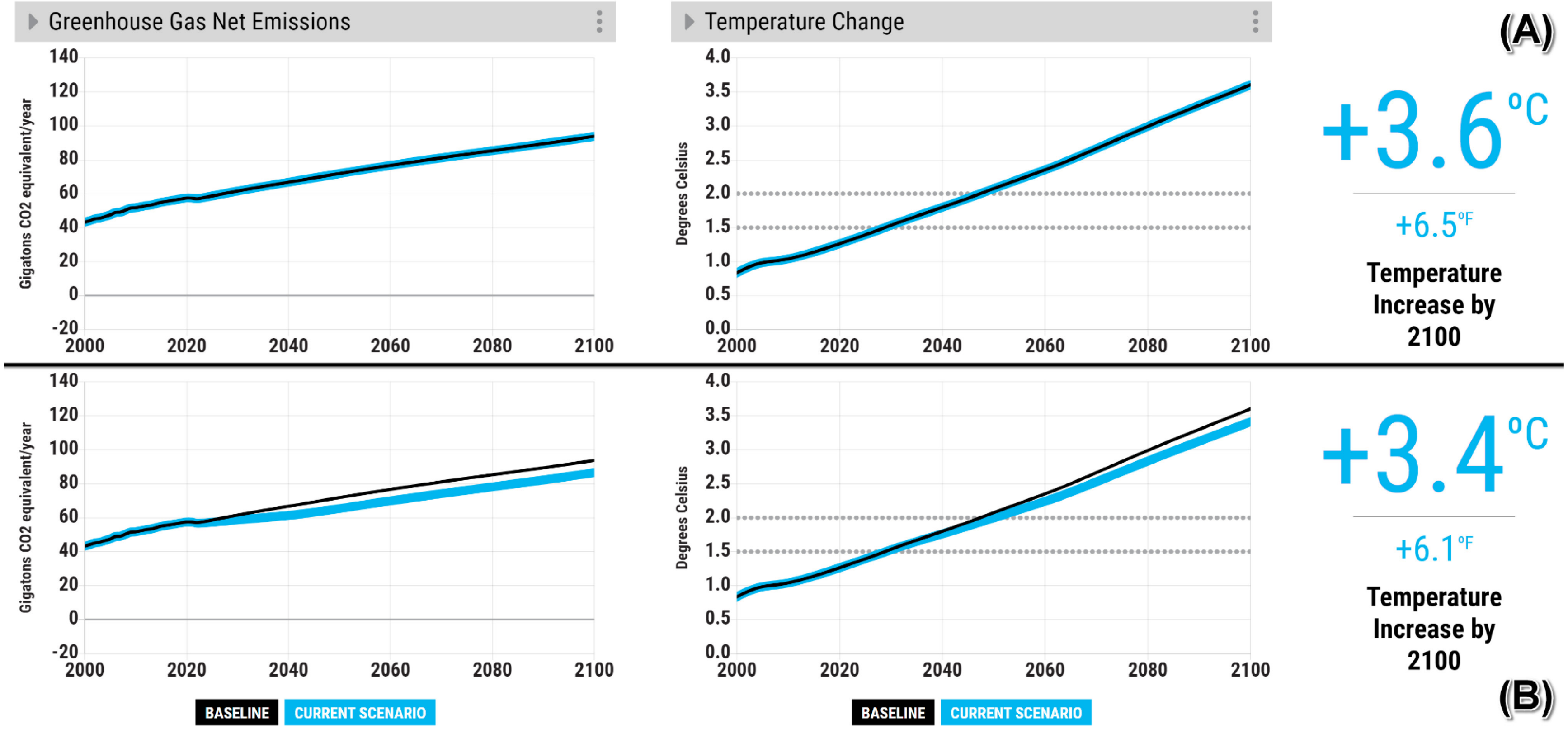


Figure 3. Comparative impact of (A) a business-as-usual scenario and (B) complete removal of agricultural (crop and livestock) and waste emissions of CH_4 and N_2O scenario on greenhouse gas emissions and temperature change. Scenario B was obtained by assigning –100% to the 'Agricultural and waste emissions' in the 'Methane and Other' in the 'Land and Industry Emissions' tab). Simulation conducted with En-ROADS version 21.9 (https://en-roads.climateinteractive.org/scenario.html?v=21.9.0)[59]

the 1.5°C maximum set by the Paris Agreement[33]. When the agricultural and waste emissions of CH_4 and N_2O were assigned a –100% maximum action[i], 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 [27] that removal of animal agriculture could reduce 68% of CO_2 emissions is in 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 versus 2.2%, respectively), and yet, it had little impact on the temperature increase, suggesting that current extreme measures to decease 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 in 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. [74] recommended 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 US and worldwide? Moreover, perhaps, more importantly, will it pay off to decrease high-quality meat production from beef cattle to offset 2.2% of CO_2e from that sector in the US, or are there other CO_2e sources that are a much higher priority to mitigate in the United States 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,[81] and little to nothing has been done since then to decrease its impact—what about using shared mobility?[82] 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.[139] Needless to say, the provocative 'having one fewer child' action was not well received.[91; 125] Furthermore, although White and Hall [134] indicated that eating plant-based diets could reduce GHG emissions, 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 sensationalized concerns together[40] 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 rather than drawing conclusions based on misunderstandings and "hidden agendas." Comparing the US beef cattle emissions of CO_2e to the total emissions of smaller countries like Portugal, Sweden, or Switzerland is senseless and out of context, and yet, it is the type of fanfare disseminated through the popular press. Similarly, the ideology that current meat consumption needs to decrease by 75%[47] to prevent Earth's global warming seems extreme and too esoteric, given the limited impact estimated by current computer models (e.g., En-ROADS) and possible nutrient deficits in human diets. The rapid increase in monoculture land use and the number of domesticated animals raised to provide food to humans have made some scientists[75; 133] concerned about the loss in biodiversity. But, livestock production does much more than simply provide high-quality protein foods to humans.[56] From a big-picture scenario, at the worldwide level, livestock sustains smallholder livelihood by giving food and increasing human health, assisting with the farming workload, improving dryland uses, sequestering C into the soil associated with the grasses grown to support them, and serving as models for the development of pharmaceutical compounds for human use, among many other benefits.[12; 18; 116] 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 to 60% of protein consumption globally.[34] 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 to the untrained eye.

From a different perspective, livestock production is not immune to the harmful effects of climate change (i.e., global warming), including impairments on the animal growth rate, meat and milk yield and quality, egg yield, weight, and quality, reproductive performance, metabolic and health status (welfare), and immune response.[86] Thornton et al. [117] 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 thermal resistant,[66] 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.[109; 111]

Since the beginning of the industrial revolution in the 18th century, agriculture has shifted its mode of action from subsistence to productivity, leading to environmental alterations unimaginable (perhaps mostly ignored) at that time. Given the direct relationship between N fertilization and crop productivity, the use of fertilizers, especially N, grew exponentially after the mid-20th century.[132] The extraordinary productivity of crops that resulted from increased fertilization was not free of problems; it resulted in different forms of nutrient pollution, especially when malpractices and poor management were involved because of the lack of nutrient management plans. Because today’s agriculture is still rooted in the high-yield mindset, it will require solid incentives and education to change the mentality towards agricultural sustainability, in which GHG mitigation and soil health become the new focus. A business-as-usual scenario for food production will continue to potentially harm the environment, but changes are possible.[87]

Methane 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 obtain an estimate of global emissions. Many methods and techniques are used to determine 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.[42; 60; 64; 105] They are designed for different production scenarios, each having strengths and weaknesses,[42; 61; 62] and the data cannot be compared directly especially when they are used outside of their intended purpose. Despite similarities of different techniques to measuring CH_4 emissions,[64] most comparisons are limited to few animals (i.e., may not be representative), 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[51]) that do not occur in real conditions. 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. For example, in an analysis of 397 peer-reviewed studies that used respiration chambers (55%), SF_6 (38%), and headstall (7%), Della Rosa et al. [22] 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.[98; 99; 107; 112; 113] The Intergovernmental Panel on Climate Change (**IPCC**) often uses more straightforward empirical approaches to assess GHG emissions by ruminants.[54] A limitation of the IPCC's empirical approaches is that these models only work for conditions similar to those in which the equations were obtained, and future predictions rarely satisfy the statistical requirements, including the original (co)variance among variables.

Given these inherent limitations of the bottom-up approaches, a second approach has been proposed. The *top-down* approaches estimate emissions using atmospheric CH_4 concentrations (e.g., drones, towers, satellites) and transportation models to assign emissions to sources.[88] 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,[65] questions still exist about their discrepancies.[88] 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.[88] The problem is not only to identify unknown sources but also to determine how long it has been emitting unaccounted CH_4. Froitzheim et al. [36] 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.[137]

Furthermore, 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.[137] Thus, the volatile CH_4 emission from one year to another might be related to the variable exposure of peat to O_2, making peat the second most crucial GHG emitter.[19] Recent findings suggest that fossil fuel may not have been the first anthropogenic activity to release massive amounts of carbon into the atmosphere, although its contribution to the global warming phenomenon is undeniable. The drainage of peatlands to convert them into arable land seems to release considerable carbon dioxide into the atmosphere. Peatlands represent only 3% of the land surface but account for more than 30% of soil C,[92] making them the most significant natural terrestrial reservoir for C.[7] Apparently, CO_2 emissions can be reversed if the drainage stops and the land rewet.[106] Similarly, another known source of CH_4 emissions that has been consistently underestimated is water reservoirs. Harrison et al. [45] indicated that the reservoirs' emission of GHG 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. Thus, 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?

Methane Mitigation from Livestock Systems

Worldwide, significant mitigation potential might exist with production systems with low productivity indexes, such as South Asia, Latin America, and Africa.[37] In the United States and Europe, opportunities for mitigation potential exist, but in different activities such as in manure management programs, not including investing in alternative energy sources.[37] Despite inconsistencies and discrepancies in the measurement and determination of CH_4 emissions by beef cattle (i.e., ruminants in general), different interventions have been proposed to mitigate CH_4 emissions by ruminants, including nutritional, managerial, genetic (i.e., energy-efficient breeds), and reproductive approaches.[4; 6; 17; 80; 94; 115]

The majority of enteric CH_4 emissions in ruminants occur during the eructation process. About 87 to 89% of CH_4 is produced in the rumen via anaerobic fermentation, whereas the hindgut contributes only 11 to 13%.[84; 85] Although discrepancies exist in the intensity of CH_4 mitigation among different types of intervention strategies, most nutritional interventions seek to suppress or inhibit the ruminal microbes responsible for reducing CO_2 into CH_4 (methanogenic Archaea), leading to a possible shift in the ruminal microbiome. More potent interventions, such as the 3-nitrooxypropanol (3-NOP), can decrease CH_4 emissions by up to 40%,[6] but the long-term impact is still unknown such as the fate of hydrogen and if CH_4 is generated somewhere else, outside of the rumen. Nutritional management strategies might be the quickest way to offer significant impact to decrease GHG, including use of antibiotics or ionophores, bacteriophages, use of feed additives (e.g., fats and oils, nitrate salts[67], dicarboxylic acids), direct-fed microbials (i.e., probiotics such as yeast), plant extracts (e.g., condensed tannins, saponins), defaunation, essential oils (not authentic fatty acids, though), biochar (mostly *in vitro* research[68; 71; 69] with inconsistent results[70]), and vaccination against methanogens.[17; 114; 110] Although these nutritional interventions might decrease CH_4 emissions, individually, by up to 20%,[6] their potency when used in combination (sequentially, rotationally, or in parallel) is not well defined.

Some recent dietary strategies such as feeding seaweed (*Asparagopsis taxiformis*[97; 108]), phytochemical feed additives, or synthetic products (e.g., 3-NOP[50], 2-bromoethanesulfonic acid,[52; 135] and other trihalomethane compounds such as fluoroform, chloroform, iodoform, and bromoform) require additional research to address the practicality, scalability, and safety concerns.[24] Another problem is how to differentiate products/strategies that work for grazing animals versus confined animals. Other agricultural practices that can mitigate GHG emissions include manure management (on-farm source of biogas fuel), rotational grazing (sequestration of C in the soil), and feed management (decreasing the amount of nutrients fed to animals through precision feeding that can also improve water quality and more efficient use of feed).[102]

Resilience versus Sustainability

Any sustainable activity must include an acceptable balance among the three pillars of sustainability: social, environmental, and economic[116] to achieve the status of sustainability. Historical trends indicate that social shortfall and economic overshot prevent sustainability[30] because eight out of ten social indicators and five out of six ecological indicators needed to meet sustainability have been (1992 to 2015) or will likely be (2016 to 2050) violated by most countries.[32] The distinction between resilience and sustainability is needed for better planning when considering future developments. After several considerations across different fields of sciences, Tedeschi et al. [116] suggested that after a certain period of time a perturbation event occurred and output stabilization has been achieved (i.e., constant output), resilient systems tend to return to their original level of output before the perturbation event. In contrast, sustainable systems tend to stay indefinitely at the new level of output. 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 systems may need governmental/policymakers interjections within agricultural systems, whereas sustainable systems may not. Thus, sustainable systems depend on the behavior/activity of the individual, internal players of the system, and each small contribution adds up to sustainable behavior. Then, it becomes essential to highlight the achievements by the beef industry 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.

For example, global warming has had a positive contribution so far for the dairy industry. It increased milk yield by about 0.1% over 38 years,[39] likely because of the alleviation of cold stress in higher latitude regions when using the temperature-humidity index (**THI**). As expected, these authors also indicated that weather extremes have a more significant negative impact on the opposite climate region, i.e., tropical regions are more sensitive to cold extremes, whereas higher latitudes are affected the most by hot extremes. In part, it is because the biomes in the tropical areas are more adapted to handle hot weather, whereas those in the temperate regions are more designed for cold weather. The optimal condition for milk production is achieved when THI is between 65 and 69, with milk production decreasing about 3.7% per day for extreme heat (> 79 THI) or 6.1% per day for extreme cold (< 39 THI).[39] If this increase in milk yield were achieved solely because of increased average temperature and it were to be held constant after the perturbation event (i.e., global warming), then this sustainable response would be classified as responsive.[116] However, other productive and reproductive indexes should be investigated simultaneously to confirm whether global warming yields a responsive outcome to the dairy industry. Although most if not all dairies in the US and Europe are likely within the 39 and 79 THI range, Harrison [46] believes the reduction in the sensitivity of the US dairy production to extreme heat and cold was a result of improvements in management, breeding, and technology, which have decreased the vulnerability of many dairy producers to *intempéries.*

Different species might also respond differently regarding climate-related issues even within the same taxonomic rank. For example, Jägermeyr et al. [57] employed the latest crop and climate models to assess comparatively cereal grains' responses to global warming. Despite corn and wheat being from the same *Poaceae* (or *Gramineae*) Family, Jägermeyr et al. [57] found out that corn productivity could decrease drastically, whereas wheat could actually benefit from higher CO_2 concentrations associated with global warming sooner than previously thought.

Human Health and Nutritional Aspects

Food choices can negatively affect human health and the environmental burden to produce them from a human health perspective, but a generalized conclusion does not apply. Negative consequences of consuming animal products are often conflated with the environmental effects of livestock production. Unfortunately, convoluted concepts and ideas have impregnated high levels of different scientific communities by mixing environmental issues with human nutritional preferences and the incidence of metabolic diseases, often leading to uncomfortable, disjointed, and disparate recommendations.[136] Clark et al. [14] 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. Such a broad assertion is complicated because many other factors must be considered, and a wide-ranging generalization like this one is undoubtedly risky in itself. For instance, the lower environmental burden of "healthier foods" depends on the C footprint for transportation, processing, retailing, and food preparation,[48] especially for those foods flown into the US.

From a human nutritional perspective, different interpretations of the data have led to divergent recommendations about consuming unprocessed red meat and processed meat.[9; 58] In late 2015, the World Health Organization (**WHO**[ii]) ruled that the consumption of processed meats should be limited because it increases the risk of cancer. The WHO's International Agency for Research on Cancer (**IARC**) 's working group evaluated more than 800 epidemiological studies published in several countries. Bouvard et al. [9] indicated an association between high 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. Other studies reached similar conclusions that the consumption of red meat has no association with a higher incidence of coronary heart disease and *diabetes mellitus*.[79] Harcombe et al. [44] and Johnston et al. [58] 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. Systematic reviews and analysis of published cohort studies with at least 1,000 participants[142; 141] found an association between reducing unprocessed or processed red meat intake and all-cause mortality and cardiometabolic outcomes. The quantitative analysis included 55 cohorts with 4.2 million participants; all but one were from North America (32.7%), Europe (38.2%), and Asia (27.3%). They found that when intake of red and processed meat was decreased by three servings per week (assuming each serving of unprocessed red meat was 120 g, processed meat was 50 g, and mixed unprocessed red and processed meat was 100 g),[141] which corresponded to the elimination of red and processed meat from the typical

North American and Western Europe diet, the magnitude of association with all-cause mortality and adverse cardiometabolic outcomes was minimal, and the evidence was of low certainty. Like other studies, they acknowledged the limitations of their results, which are the inability to adequately adjust for known confounders, residual confounding resulting from observational design, and recall bias associated with dietary measurement. At least part of the difference between the Zerraatkar and collaborators'[142; 141] findings of a small and low certainty of association with adverse cardiometabolic outcomes and strong and consistent US Department of Health and Human Services (**USDHHS**[iii]) and US Department of Agriculture (**USDA**[iv])[123] findings of high risk for cardiovascular disease for those consuming red meat may be a result of differences in the databases used. The USDHHS and USDA database included sources determined to represent the US population, whereas the Zerraatkar and collaborators'[142; 141] database was from an international search of which only 32.7% of the studies were from the US and Canada. This database raises the question of the applicability of the Zerraatkar and collaborators'[142; 141] findings to the US population because it is 67% overweight or obese, and 38% are sedentary.

Furthermore, failures to assess multicollinearity among human diseases (e.g., people who consume high levels of red meat also consume high levels of sugar; so, which one causes the disease?) 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,[140] so presumably, cardiometabolic diseases 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 diseases than the 65 to 74-year-old group,[140] and yet, the overall per capita consumption of beef has decreased since the 1970s (Figure 1B).[121] There is a need to assess illness and environmental burden for individuals who do not consume in excess. Another point of concern is that those who consume "veggies" are believed to be well-educated and food intake-watchers, whereas those who consume red meat are thought to be less likely to watch their diets and are usually leading a more extravagant lifestyle. Thus, these groups cannot be contrasted because they are by "design" different; the comparison has to be made within the groups. The environmental burden was associated with a group of excess food-eaters; thus, if high GHG emissions, then high water demand, then high soil degradation. Also, there is a need to account for different stages of growth (resulting from energy and nutrient needs): children versus adults. A fair system must be established to compare foods on their nutritive value basis: how much meat, beans, or lettuce are needed individually to meet energy and nutrient needs; then what is the GHG balance. What are the costs and arable land areas required to produce, let us say 1 kg of meat versus 2 kg of beans versus 10 kg of lettuce?—hypothetically assuming that these amounts would meet energy and nutrient needs. Although GHG emissions to produce fruits and vegetables are lower than nutrient-dense animal products (i.e., beef and milk) on a weight basis, their GHG emission on an energy basis is much greater.[25; 127] Furthermore, the land area used by beef cattle may not be suitable for lettuce production. What is the cost of making it arable and sustainable (if even possible) for lettuce production? A system analysis such as life-cycle assessment (**LCA**) analysis must be adopted to account for little details that add up in the end.

Often 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,[49] but frequently over-emphasized and twisted towards public health appeal. Few studies have looked into health issues among different dietary groups, such as the nutritional value of alternative (i.e., cultured) meats[126] or the relative consumption of synthetic pesticides, given that some pesticides used to produce food are carcinogenic or tumor promoters.[5; 23] Unfortunately, there is evidence that vegetarian eaters are more prone to ingest more significant quantities and different types of pesticide residues than omnivorous eaters.[124] Could this be the beginning of unintended consequences on worsening human health? Thus, ruling in favor or against a group of food (red meat versus veggies) is not inconsequential; it requires a more profound understanding of variables that might be unknown at this time or forgotten before 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 (food pyramid?). The considerations made by Mariotti [78] 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)." Another more recent consideration is the contribution of the production of different foods, especially vegetables and fruits, to microplastic pollution/contamination and human health.[118; 130]

A Brighter Perspective for a Longlasting Solution

As noted previously, the emphasis on the impact of beef cattle production over-states its actual contribution to climate change. As detailed by the US EPA data, all livestock accounted for 0.25 Gt CO_2e (0.1786 from enteric emissions and 0.0821 from manure management) in the United States in 2019,[29] which corresponds to about 3.98% of total CO_2e emissions in the US. Beef cattle production per se was responsible for only 2.2% of the total annual emission of GHG in the US in 2019, which translated to about 0.24% of the GHG produced in the world. 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. Earth's biosphere is responsible for most (if not all) feedback loops that control biological cycles, including C; thus, the development of biosphere stewardship[96] 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 the soil. Note that soil management accounts for 54.82% of total agricultural emissions of CO_2e (Figure 2), more than livestock per se (41.46%). However, it is only fair to note that the soil management category includes 1) application of managed livestock manure and 2) manure deposition on soils by domesticated animals in pastures, range, and paddocks,[29] sources that are clearly related to livestock production.

Perhaps the agricultural scientific community has overlooked important opportunities for addressing the climate change problem by looking at it from the wrong angle and using the incorrect (or incomplete set of) tools. The classical textbook *The Nature and Properties of Soil* by Nyle C. Brady[132] is still widely used (I also learned from it!), but I am afraid we might have been using outdated understandings of soil, its biological microsphere, and its potential [beneficial or catastrophic] impact on global warming. Better soil management might be the world's best option to combat climate change after all. Of course, achieving a more enlightened understanding will require collaboration from all fields of science, including animal scientists. The soil can be critical in solving the climate change crisis because of the potential 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 the soil depends on many more 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 to the atmosphere). The potential for soil C sequestration has often been ignored by LCA analyses;[89] thus, guidelines have been developed to assist with the determination of soil C sequestration for beef cattle production.[35] Besides weather-related (light, temperature, water) and soil genesis traits, other factors include the availability of nutrients (e.g., macrominerals and microminerals) required by the plants for growth and development, with particular attention to N. 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, more stable stocks in the soil. The understanding of the behemothic complexity of the interactions among different ecological cycles and associated signals that regulate them required 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, ignored subsoil organic matter dynamics and have been derived by small-scale research.[16]

So, how can livestock assist with the incorporation of C to more stable stock in the soil? Grazing ruminants are an essential component of the C cycle. A study at the grassland of the Yellowstone National Park reported that the grazing behavior of American Bison stimulates the growth of nutritious grass by spreading manure that acts as a fertilizer to the landscape.[38] Similarly, Allan Savory has consistently defended the thesis that grazing ruminants can stop or even reverse the desertification process[v] in some areas of the world through holistic management strategies[101] by simply letting the cattle graze and browse grasslands and spread their manure onto the soil, increasing the sequestration of C by the soil, i.e., regenerative agriculture. In fact, grazing beef cattle can be a sink by increasing the C sequestration in the soil depending on the grass management strategy.[10; 119] Long-term burning practices of grasslands used in many world regions can decrease soil organic carbon and nitrogen stocks, contributing to GHG; but when associated with rotation between burning and mowing, it might provide sustainable alternatives to grassland management.[1] Stanley et al. [103] showed that when using a rational/rotational-type grass management system[128], the 4-year 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. [129] reported a similar C sequestration rate of 3.53 Mg C/ha/yr for the ten years 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 versus 20 to 200 kg CO_2e per kilogram of protein, respectively), although the variation among LCA analyses is considerable.[89]

A systems approach has to be employed. For example, the dung beetle, an insect from the Coleoptera order with more than 8,000 species, is essential for successfully incorporating manure into the soil. But, the incorrect use of antibiotics and anti-parasitic medications might alter its biological cycle. The development and use of sustainable alternatives to synthetic products are needed. Garlic-based products have been reported to not only reduce GHG emissions,[2; 8] but also to assist in the control of horn fly,[26] leading to the reduced use of synthetic antibiotics and anti-parasitic compounds in the production system.

The Net-Zero Emission Concept Might Become Another Holy Grail in the 21th-Century

Are we losing sight of the forest because of the trees? There are too many little things in which the scientific community is focused and cannot see the big picture, much less understand how things are connected. Take the global warming conundrum as an example. Some groups are adamant that livestock, specifically ruminants, are a big player in the planet's global warming. Others resist this notion by trying to shed some light through scientific discourse. However, the pendulum seems to be swinging farther to the big player side.

Definitions abound when it comes to concepts related to solving the climate change or 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.[55] Although the industry and governments increasingly recognize the net-zero concept, it is far from being 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.[31] In principle, the net-zero emission concept will not solve the global warming problem; it will put global warming on a standby state because we will 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 [73] seem to indicate that even under a net-zero condition, global warming will continue increasing because of the inertia of Earth system feedbacks such as ocean temperature and permafrost thawing’s C release rate. In reality, global warming needs 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.

Some advocate that there is no new release of C by ruminants; therefore, they are not to be blamed for global warming—there is no increase in the worldwide temperature because CH_4 being eructated by ruminants is part of a cycle. That means the C is present in different forms (either CH_4 or CO_2 or $C_6H_{12}O_6$) 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.[104] The second step is to identify important state and rate variables (i.e., stock and flow variables) to the problem.[104] Another point is the time step needed to simulate the dynamics of the problem. For an animal, one year is too much time, but for climatic events, it is not. 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 and over, in one form or another over time. 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[112] join the CH_4 produced by many other sources in the troposphere where they are short-lived as 85% reacts with OH in the presence of sunlight ($CH_4 + OH \rightarrow H_2O + CH_3$).[13] 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.[13] The other 15 to 20% is transported upward to the stratosphere and destroyed.[13] 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 glucose ($C_6H_{12}O_6$)[11; 93] that can be further converted to other more complex structures such as cellulose. Herbivores, including ruminants, consume these carbohydrates, 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).[20; 100] This exergonic process serves as the terminal acceptor for the methyl group and allows for ATP synthesis.[20; 100] 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. The bottom line is that because no new C is released into the atmosphere by ruminants when their population is relatively stable: they cannot be blamed for increasing global warming. In the case of the US, 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 US 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[112; 113] was used to estimate the average CH_4 emission, while 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., feedlot, dairies), using tractors and other types of machinery that use petroleum. In general, fossil fuel combustion is a process that does release new C into the atmosphere; therefore, a fundamental contributor to global warming. The question becomes

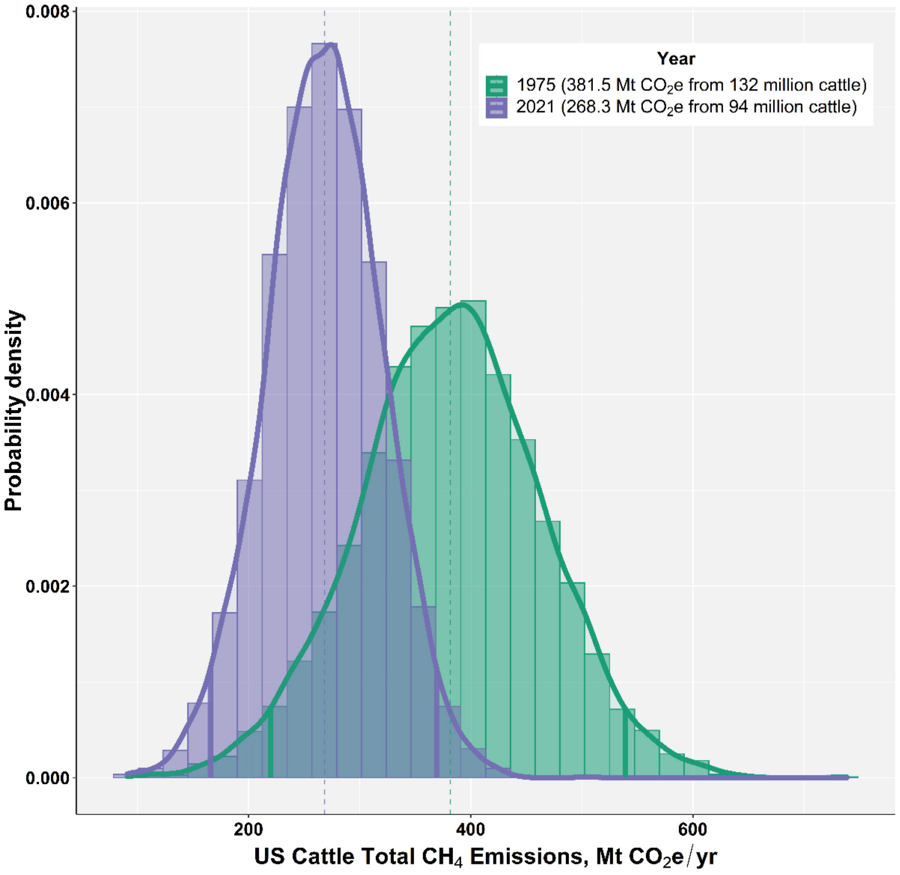


Figure 4. Simulated distribution of total methane production by the cattle herd in 1975 and 2021, assuming average and standard deviation of predicted daily methane production for beef and dairy cows and feedlot animals consuming typical diets. The 95% confidence intervals (vertical segments under the 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 productions were conducted with the Ruminant Nutrition System using the mechanistic and empirical levels of solution.[112; 113]

whether this new C should be assigned to feedstuff production or the animal operation that directly benefits from the feedstuff. This is complicated because if the feed does not go for animal production, it could technically be used for human consumption (at least partially). However, humans cannot consume corn silage or hay (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 better to feed animals and use animal products for human consumption, or use the cereal grain directly 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 United States; thus, its elimination would do little to address the climate change problem. Many different dietary interventions might decrease (or even eliminate) the GHG contribution of beef cattle, but besides being an esoteric measure, it is unclear at what price this approach is economically viable. Additionally, significant reduction or complete removal of red meat might result in unintended consequences and worsen human health given the increased pesticide consumption of plant-based diets. Selection for efficient and resilient animal breeds and consumer education seem to be the top priorities for genuinely sustainable beef cattle production in the US. Additional measures include dietary interventions of ruminant animals to minimize or mitigate CH_4 output and emissions, reducing food waste losses by developing and adopting more efficient logistics (e.g., transportation), locally produced, 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 emission by beef cattle, and producers are willing and ready to employ them sustainably. Furthermore, meat is a staple food in many developing countries, given its nutritious value in meeting human protein needs. Perhaps, it is time for consumers and bystanders to acknowledge the importance of the US beef industry, given its past, present, and future commitments to society and the environment.

List of Abbreviations

CO_2e: equivalent CO_2; **COP**: conference of the parties; **En-ROADS**: Energy-Rapid Overview and Decision Support; **GHG**: greenhouse gases; **Gt**: Gigatons; **GWP**: global warming potential; **IARC**: International Agency for Research on Cancer; **IPCC**: Intergovernmental Panel on Climate Change; **LCA**: life-cycle assessment; **Mt**: Megatons; **Tg**: Teragram; **THI**: temperature-humidity index; **USDA**: US Department of Agriculture; **USDHHS**: US Department of Health and Human Services; and **WHO**: World Health Organization.

Acknowledgments

The author greatly appreciates the feedback received by researchers and colleagues during the preparation of this manuscript, in particular, Dr. Danny Fox (Cornell University), Dr. Michael Galyean (Texas Tech University), Dr. James Oltjen (University of California-Davis), and Dr. Karun Kaniyamattam (post-doctorate at Texas A&M University) and many graduate students. They read the manuscript with great enthusiasm, given their passion for animal agriculture.

Funding Support

The author acknowledges the financial support of the USDA-NIFA Hatch #09123 "*Development of Mathematical Nutrition Models to Assist with Smart Farming and Sustainable Production*" that sponsored data gathering and literature review necessary to assemble this manuscript.

Conflict of Interest Disclosure

The author declares no financial conflict of interest with the content of this manuscript. LOT is an advisor to animal operations and agribusiness industries.

Data Availability

Data are available under request for academic purposes on the Zenodo data repository (https://doi.org/10.5281/zenodo.5944737).

Ethics Approval

No live animal was used in this manuscript.

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