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LETTER

Net zero initiative in U.S. beef and dairy systems: integrative on-farm recommendations for greenhouse gas reduction

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Abstract

Beef and dairy production systems play an important role in society, providing a variety of ecosystem services. U.S. beef and dairy production systems require being aligned with the global and national effort to stabilize the anthropogenic greenhouse gas (GHG) emissions in the atmosphere. This study adapted the nominal group technique framework to design a roadmap to achieving a net-zero GHG cattle supply chain in the U.S. with an emphasis on farm recommendations. Scientists with diverse expertise in sustainable beef and dairy production proposed, categorized, described, defined, and prioritized strategies that have the potential to significantly reduce GHG emissions, improve production system efficiencies, and promote sustainability. These strategies were presented to different stakeholders and classified according to the marginal GHG reduction, expected return on investment, and market readiness. Thus, strategies were defined for cow-calf and stocker, feedlot, and dairy operations, according to the characteristics of the cattle systems in the U.S. This net-zero roadmap presents a broad range of options for promoting sustainable cattle production in the U.S. Priority items for a research agenda to facilitate progress towards implementing this net-zero roadmap are described according to the dairy or beef production system and including the modulation of rumen fermentation, precision diet management, manure management, increasing animal and system efficiency, and genetic evaluation and selecting of efficient animals. The expected return on investment and market readiness of the proposed strategies depend on the technology type and system localization. Progress toward the net-zero goal depends on the widespread adoption of appropriate mitigation strategies. Future research programs must prioritize identified research needs to promote the wide adoption of the proposed strategies.

1. Introduction

Carbon-based anthropogenic activities are related to increasing atmospheric greenhouse gas (GHG) concentrations, which are modifying natural cycles and impacting human communities (Forster *et al* 2021).

Ruminant production plays an important role in society by providing a variety of ecosystem services, such as converting non-human edible plants to high-quality protein, conserving non-arable lands, maintaining cultural heritage and aesthetic landscapes, rural community well-being, water regulation, etc (Herrero *et al* 2013). Ruminants produce 7.4% of the total global anthropogenic GHG, where methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) represent 54, 15, and 31% of the livestock GHG emissions, respectively (FAO 2023). Worldwide, there is an emergent objective to reduce GHG emissions associated with ruminant production to promote carbon-neutral systems (Herrero *et al* 2016).

Within the U.S. beef and dairy production systems, the net zero initiative is aligned with the global effort to stabilize the anthropogenic GHG emissions in the atmosphere. Net zero is defined as the neutral balance between the GHG emissions produced by a system and the anthropogenic GHG removals, and it usually assesses the full life cycle of a product, including Scope 3 emissions (Masson-Delmotte *et al* 2022). Therefore, recognizing the emissions sources and alternatives to reduce GHG emissions from ruminant systems is essential to achieve net zero. Proposed management strategies should reduce GHGs and concurrently maintain or ideally improve animal productivity. Management strategies that reduce productivity and profitability will have very low adoption by producers (Arndt *et al* 2022).

Estimated emissions of GHG from ruminant production in the U.S. have increased 19% since 1990 (EPA 2024). The primary drivers of ruminant agriculture GHG are 1) enteric CH_4, where beef cattle are the primary contributor due to their large population numbers, with estimated emissions increasing 6% since 1990, and 2) CH_4 from manure where dairy cattle are the most prominent contributor due to their standard confined feeding operations where manure management and storage systems are used to apply manure on nearby cropland soils, with estimated emissions increasing 62% since 1990 (EPA 2024). Both beef cattle meat production and dairy cattle milk production have increased since 1990 as well, resulting in a decrease in the carbon footprint per unit of these products (i.e., emission intensity) (Capper and Cady 2020).

Beef cattle production occurs across all 50 U.S. states and it is the single largest segment of agriculture. The number of operations with beef cattle has declined over time, with 1.03 million farms with beef cows in 1986 to 730,000 operations today (USDA 2024). In addition, beef cow-calf operations have largely avoided the trend of consolidation (Drouillard 2018). Consequently, estimating and mitigating GHG emissions from beef production, particularly cow-calf production, can be challenging as it involves hundreds of thousands of farms and is raised largely on pasture/rangeland, where mitigation is very difficult to employ.

U.S. beef cattle production is responsible for approximately 243 million metric tons annually of CO_2 equivalent (CO_{2e}) emissions. The major contributor to these emissions was enteric CH_4, representing 56% of the total footprint (Rotz *et al* 2019). Nitrous oxide from managed manure and pasture, range, and cropland soils represented 23% of the footprint (Rotz *et al* 2019). The cow-calf and stocker phases contribute a majority of these emissions due to the higher number of animals from these sectors and the higher enteric CH_4 emissions per animal when cattle consumed forage-based diets (Beauchemin *et al* 2022).

Similarly to beef cattle production, dairy cattle also occurs across all 50 states of the U.S.; however, milk production and dairy cattle numbers are more concentrated than beef cows, with the top 5 dairy states (i.e., California, Wisconsin, Idaho, Texas, and New York) containing 52% of the dairy cow herd (USDA 2024). In addition, the U.S. dairy industry has consolidated, with the number of farms declining from 125,041 in 1997 to 36,024 in 2022, while the number of dairy cows has increased from 9.1 to 9.3 million during the same period, respectively (USDA 2024). As herd sizes on the remaining dairy farms have increased, management practices have changed, with fewer farms utilizing grazing lands and increasing manure management and storage systems to better apply manure nutrients to cropland soils. These manure management changes largely explain the increase in GHG emissions from the dairy cattle industry, particularly in CH_4 emissions from dairy cattle production (Rotz *et al* 2010).

The largest source of GHG emissions from U.S. dairy cattle production is enteric CH_4 emissions, representing 43% of the total 99 million metric tons of CO_{2e} emissions (EPA 2024). Enteric CH_4 is the most significant contributor to GHG emissions on-farm and has increased over time. In addition, manure CH_4 emissions also contribute significantly to GHG emissions from dairy production but are more variable based on region and manure management practices (Rotz *et al* 2010). However, in recent years, manure emissions have been increasing more rapidly than enteric emissions from the dairy sector due to these changing manure handling practices (EPA 2024).

Identifying management strategies for a roadmap to achieve the net-zero initiative and a prioritized research agenda to reduce GHGs from beef and dairy cattle in the U.S. is needed. Therefore, a facilitated process was undertaken, with experts from a variety of disciplines related to sustainable beef and dairy production, as well as dairy and beef producers, consulted to identify and classify strategies according to their efficacy for reducing GHG, potential adoption, and market readiness. This document described the identified and prioritized strategies according to the dairy or beef production system and defined research areas to promote the wide adoption of the proposed strategies.

2. Materials and methods

This study adapted the nominal group technique (NGT) framework to design a roadmap to achieving net zero cattle production in the U.S., encompassing beef and dairy sectors. The process involved two facilitators and an expert advisory panel comprising 11 scientists with diverse expertise in sustainable beef and dairy production. It spanned 18 months (from June 2022 to November 2023) and unfolded across four phases. This application of the NGT framework is similar to the procedure discussed (Humphrey-Murto *et al* 2023) and previously adopted (Cook *et al* 2023).

In the first phase, virtual meetings were held with the expert advisory group to identify and discuss strategies for reducing GHG emissions in U.S. beef and dairy production. This phase encompassed four key activities:

i) Round-Robin group discussion: Each member of the expert advisory group had an opportunity to speak in a structured manner, raising ideas, concerns, and questions regarding the roadmap's scope, goals, target audience, and stakeholders. The aim was to narrow down the primary objectives of the roadmap, the intended audience, and key stakeholders impacted by the proposed strategies.

ii) Brainstorming strategies: Each member categorized their ideas into three groups—most feasible, least feasible, and uncertain—for reducing carbon emissions in U.S. cattle production. Strategies were further classified by production type: cow-calf stocker/backgrounder, finishing, and dairy. Subsequently, facilitators organized the ideas into spreadsheets, with each spreadsheet dedicated to a specific production type.

iii) Description of strategies: Members of the advisory panel provided individual descriptions of the brainstormed strategies. These descriptions aimed to clarify the proposed actions resulting from the brainstorming activity.

iv) Virtual consensus meeting: The expert panel convened to discuss and refine the strategies and their descriptions. Consensus was reached on classifying strategies as most feasible, least feasible, or uncertain and describing each strategy. To ensure accessibility for diverse audiences, the descriptions focused on using less technical language, reflecting the varied expertise within the group.

Three virtual meetings were held during the second phase, featuring tournaments between the ideas proposed using a double-elimination structure. The facilitators organized these tournaments and utilized the poll voting tool within Zoom software (version 5.17.7), allowing participants to vote on strategies they deemed most feasible and effective in reducing emissions. Participants emphasized the importance of having strategy descriptions available in the spreadsheets, enabling voters to understand the exact meaning of each strategy fully. The main objective of the tournament was to establish a priority ranking of the proposed strategies, thus simplifying the organization of the roadmap. The ranked ideas were subsequently categorized into short-, mid-, and long-term implementation. Following the virtual meetings, the advisory group engaged in an asynchronous collaboration process to review the strategy ranking and classification, ensuring the feasibility of the preliminary roadmap design.

Phase three comprised six facilitated meetings with separate focus groups for each sector: cow-calf stocker/backgrounder, dairy, and finishing. These meetings aimed to engage producers in discussions regarding the feasibility of strategies within their respective sectors and to refine the initial strategy outlined in the preliminary roadmap design. Participatory discussions on the feasibility of proposed strategies were widely adopted, ensuring alignment with the realities and objectives of the producers (Proudfoot *et al* 2022). This collaborative approach enables stakeholders to provide valuable insights and perspectives, ultimately enhancing the relevance and effectiveness of the proposed roadmap.

Phase four culminated in categorizing strategies based on their projected impact on reducing GHG emissions, expected return of investments (ROI), and market readiness. This process yielded a final list of strategies with the potential to propel the beef and dairy sectors toward achieving a net-zero goal in the future. Three key criteria guided the categorization:

1) Marginal GHG reduction: Strategies were prioritized based on their potential to reduce GHG emissions compared to those significantly less impacted. Strategies were classified as high, medium, and low. In figures 1–3, the classification of high, medium, and low was considered 10, 5, and 1, respectively.

2) Potential ROI: Strategies with potential profitability for producers upon implementation were prioritized, surpassing those with uncertain or no ROI. Strategies were classified as yes, neutral, and unknown. In figures 1–3, the yes, neutral, and unknown classifications were considered 10, 0, and 1, respectively.

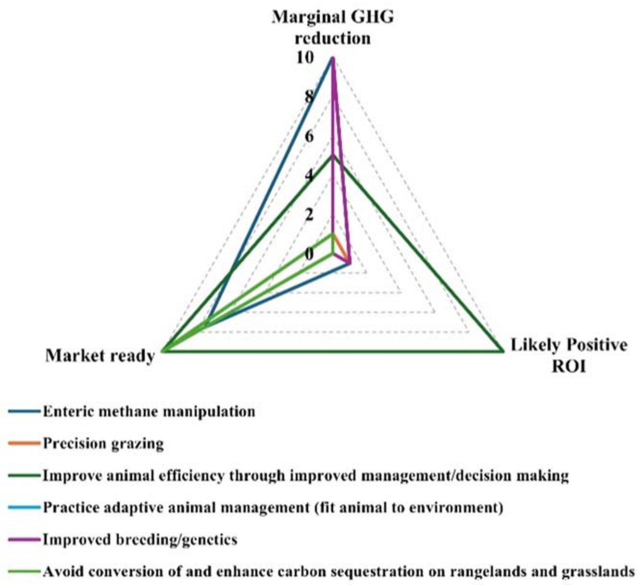

Figure 1. Prioritized strategies in the net zero initiative for cow-calf and stocker operations in the U.S.

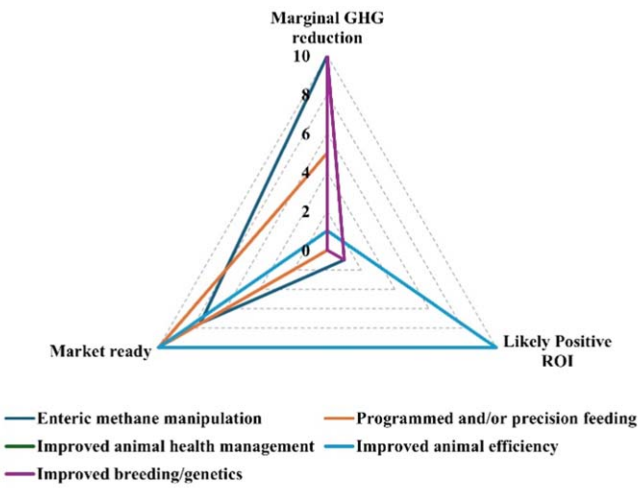

Figure 2. Prioritized strategies in the net zero initiative for feedlot operations in the U.S.

3) Market readiness: Strategies readily available in the current marketplace were favored over those not yet accessible. Strategies were classified as yes, no, and almost. In figures 1–3, yes, no, and almost classification was considered 10, 0, and 5, respectively.

This systematic approach ensured that the selected strategies were effective in reducing emissions and financially viable and readily implementable, facilitating progress towards the net-zero goal in the beef and dairy sectors. The NGT approach facilitated collaborative decision-making and the development of a comprehensive roadmap for achieving net-zero cattle production in the U.S., encompassing both beef and dairy sectors.

3. Results

3.1. Prioritized strategies to promote the net zero initiative in the beef cow-calf and stocker sector

Key strategies identified to help the industry move towards net zero emissions from the cow-calf and stocker sectors were related to enteric CH_4 manipulation, grazing and animal management, breed selection, and carbon sequestration (figure 1). Rumen modulators such as feed additives or vaccines would reduce enteric CH_4 emissions, but the economic implications and technology availability are unknown at this time. Supplementation under grazing conditions presents challenges due to the variety of grazing systems utilized

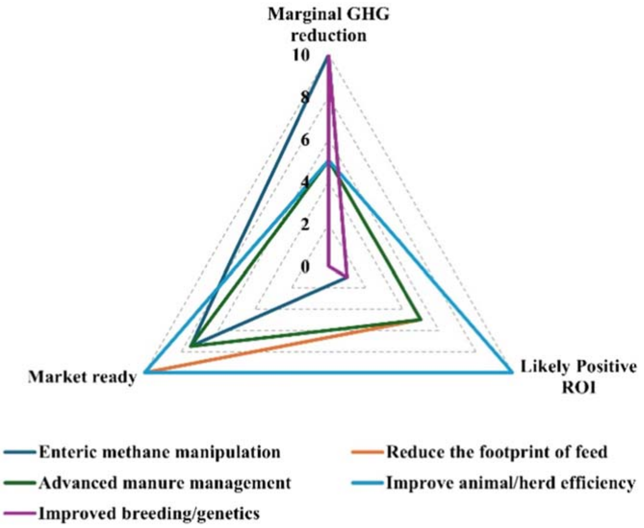

Figure 3. Prioritized strategies in the net zero initiative for dairy operations in the U.S.

across the U.S., delivery aspects of the products, consumption rates and visits by grazing animals, product stability under variable weather conditions, etc Precision grazing management has a low potential to reduce GHG emissions even though it is available to producers as the economic implications of adopting management practices such as virtual fencing remain unknown.

Animal management, such as implants, has medium potential for reducing GHG emissions as they improve animal growth efficiency, are readily available, and show positive economic returns. Breed selection based on characteristics such as climate tolerance or less nutrient excretion has a high potential to reduce GHG, but the economic implications are unknown, and the sector must be willing to invest time and resources in defining the parameters for regional selection appropriateness. Carbon sequestration through avoiding the conversion of grazing landscapes to croplands has a low potential to reduce GHG emissions, but this strategy is available for producers and has neutral financial implications.

Experts defined two intermediate strategies for promoting net zero cow-calf and stocker systems (Table S1). Increasing nitrogen use through precise fertilization application to pasture/croplands or incorporating adapted plant germplasm for pastures/cover crops has medium potential to reduce GHG and is available for use. The economic implications of adopting those technologies for efficiently using nitrogen need additional effort, however. Promoting the conservation of formerly cropped or degraded lands to improve pastures is being used currently and has medium potential to reduce GHG with neutral economic implications.

Other strategies with lower potential for promoting net zero systems are related to grassland and animal management and creating renewable energy (Supplement table 1). In this regard, using perennial forages and reducing tillage in forage and feed-crop production systems have a low potential to reduce GHG emissions. However, those strategies are available for producers, although the economic implications are unknown and might vary according to farm conditions. Similarly, the Conservation Reserve Program (CRP) promotes appropriate grazing, which has a low potential to reduce GHG emissions. Although this program can be economically attractive, it is unavailable to all producers.

From an animal perspective, adaptive management of stocking rates according to forage availability has a low potential to reduce GHG emissions but positive economic returns. Confined cow-calf production has a high potential to reduce GHG emissions and is available, but the financial and social implications of this strategy are unknown.

Adding renewable energy at the production system level, such as installing solar photovoltaic (PV) panels or wind turbines, is available and can provide economic returns to producers, but this has a low potential to reduce GHG emissions.

3.2. Prioritized strategies to promote the net zero initiative in the feedlot sector

The most important strategies for promoting a net zero initiative from the feedlot sector were related to enteric CH_4 manipulation, feeding and animal management, and breed selection (figure 2). Using enteric CH_4 modulators has a high potential to reduce GHG gas emissions, but the availability and economic implications are unknown. Implementing precision feeding practices has medium potential for reducing GHG emissions and is currently available for feedlot producers with neutral financial implications.

Fostering animal health and implementing practices to increase animal efficiency have a low potential for reducing GHG emissions, but positive economic returns occur. Animal genetic selection has a high potential for reducing GHG emissions but is limited availability at this time, and unknown financial implications are present.

Other strategies include feed ingredient acquisition, manure management, and generating renewable energy (Table S2). Reducing the carbon footprint of feed resources and using byproducts have medium potential to reduce GHG emissions, and they are already available for feedlot producers. However, the financial implications vary according to cultural and industrial practices in feed production and feedlot location. Manure management has a low potential for reducing GHG emissions as manure management is already occurring with positive economic returns. Adding PV panels or wind turbines has a low potential to reduce GHG emissions even though this technology is available and economic returns are positive.

3.3. Prioritized strategies to promote the net zero initiative in the dairy sector

The most important strategies for reducing GHG emissions from the dairy sector were related to enteric CH_4 manipulation, reducing feed ingredient footprint, animal and manure management, and genetic selection (figure 3). Manipulation of enteric CH_4 has a high potential to reduce GHG emissions, as stated previously. The use of feed ingredients with a lower carbon footprint and byproducts as feed, which enhances system circularity, has medium potential to reduce GHG emissions. These strategies are available, but financial implications are variable and depend on the availability of feed and the location of the dairies.

Animal and manure management have medium potential to reduce GHG emissions. Strategies in these sectors include improving herd efficiency through improved health management, precision feeding, heat stress mitigation, and genetic improvements to the herd, as well as the implementation of a suite of technologies to improve manure management, such as enhanced separation systems, anaerobic digestion, nutrient capture systems, etc Practices to promote animal efficiency are available with positive returns. The availability of manure management technology varies, and advanced treatment systems are expensive, resulting in unknown financial implications. Improved breeding and genetics have a high potential for reducing GHG emissions, but limited selection programs are available, and economic aspects are unknown.

Other strategies for fostering the net zero initiative in the dairy sector are associated with increasing nitrogen use efficiency, promoting carbon sequestration, optimizing the beef and dairy systems, and creating renewable energy (Table S3). For example, optimizing beef and dairy production by integrating beef genetics into dairy to increase the value of calves going to the beef sector has a low potential for reducing GHG emissions, although practices are currently available for dairy producers and show positive economic returns. Adding PV panels or wind turbines has a low potential to reduce GHG emissions even though this technology is available and economic returns are positive.

4. Discussion

The proposed net zero initiative roadmap is well-positioned for successful implementation (Bizikova *et al* 2009). The participatory approach implemented in this study considered multiple interests and different perspectives to increase the likelihood of implementing practices for reducing GHG (Bell *et al* 2012, Cloutier *et al* 2015, Campos *et al* 2016). This approach promotes transparent decision-making, which builds trust among stakeholders and ensures that decisions are based on evidence, data, and stakeholder input, thereby enhancing accountability (Fazey *et al* 2014, Groot *et al* 2015, Glaas *et al* 2017) and evaluating priorities, trade-offs, and potential conflicts associated with different mitigation strategies (Kettle *et al* 2014, Luís *et al* 2018).

The participatory approach employed in this study was the NGT, which consists of a structured group decision-making process designed to foster equal contribution from all participants and facilitate the generation and prioritization of ideas or solutions to a given problem. This consensus-building process is crucial in climate change decision-making, where stakeholders might have competing interests and priorities. The NGT provided a transparent and documented process for decision-making, which is essential in the context of climate change policy development. The structured approach ensured that all ideas were recorded and the reasoning behind prioritizing solutions was clear and justifiable. The structured process also helped to keep discussions focused and ensured that the group progressed toward a set of prioritized solutions (Boddy 2012, Rankin *et al* 2016, Humphrey-Murto *et al* 2023)

As products of the participatory approach implemented in this experiment, the consulted experts defined and prioritized different strategies for promoting the net zero initiative for the U.S. beef and dairy production systems. Approaches for reducing enteric and manure CH_4 emissions represent a large proportion of the prioritized strategies. Methane is a product of the anaerobic fermentation of the organic matter during the digestive process or manure handling (Montes *et al* 2013, Beauchemin *et al* 2020). Different mechanisms to reduce enteric and manure CH_4 emissions have been proposed in the literature (Hristov *et al* 2013, Montes *et al*

2013, Beauchemin *et al* 2022). Rumen fermentation modulators to reduce enteric CH_4 showed a high potential to reduce CH_4 emissions from different sectors (figures 1–3). However, there are limited options available for producers, especially under grazing conditions, and it is necessary to evaluate the profitability and life cycle assessment of each alternative (Arndt *et al* 2022, Vargas *et al* 2022). Modifying dietary characteristics through improving grazing management and precision feeding could result in more efficient fermentation, reducing the energy losses as CH_4 (Arndt *et al* 2022, Galyean and Hales 2024). Improved manure management according to production system type and region represents a prioritized strategy for reducing manure CH_4 and N_2O emissions, especially in confined production systems (Chadwick *et al* 2011, Montes *et al* 2013) (figure 3).

Improving animal and herd efficiency through implementing practices such as increasing productive days or reproductive performance represents a strategy to reduce GHG emissions by lowering the required days and the number of animals to support the meat and dairy value chain (figures 1–3). Emissions of GHG could potentially be reduced by 30% when efficient animal management practices are incorporated into the cattle systems (Gerber *et al* 2013). However, implementing efficient practices requires the continued involvement of different stakeholders, such as extension specialists and producers, and the development of new technologies able to adapt to various production conditions. Furthermore, experts suggested that the confinement of cow-calf operations and the optimization of beef and dairy production allow better efficiency and allocation of CO_2 emissions, potentially reducing GHG emissions; however, it is necessary to comprehensively evaluate the tradeoffs of those strategies according to the production systems, environmental conditions, and social preferences.

Selecting more efficient or low CH_4 emitting animals represents a prioritized strategy that would result in lower GHG emissions from the cattle industry (figures 1–3). Animal genetic evaluation requires considerable effort and resources from the beef and dairy sector to identify animals with desirable characteristics (Beauchemin *et al* 2020). However, it is unclear whether the potential change in production efficiency as a single-criteria selection in genetics results in a myriad of unintended consequences. Producers could incorporate this strategy once selection criteria are available. Likewise, it is necessary to determine the appropriate measures, techniques, and protocols to develop a proper evaluation program.

Avoiding the conversion of rangelands and grasslands to croplands or housing is a prioritized strategy to provide continued opportunities for these lands to be GHG sinks (figures 1–3). Land conversion from grassland to croplands or inappropriate soil management can increase CO_2 losses (Conant *et al* 2017). In addition, the carbon footprint from feed production shows high variability related to cultural practices and origin. These strategies promote greater carbon accumulation, especially in sensitive landscapes, and the incorporation of ingredients with lower GHG emissions in the diets of ruminants, respectively. In addition, experts suggested that implementing technology to generate renewable energy for beef and dairy operations could result in lower GHG net production in the sector. However, more information is required regarding the trade-offs of this technology in the system and how the implementation affects profitability.

Implementing practical recommendations for reducing GHG in the beef and dairy sectors in the U.S. may result in synergetic consequences on the provision of ecosystem services that were not considered in this analysis. For example, greater CO_2 accumulation due to appropriate grazing management can result in not only a reduction in GHG emissions but also an increase in water soil retention and improved soil fertility (Teague and Kreuter 2020). Additionally, the dynamics of the dairy and beef cattle systems in the U.S., such as the consolidation of some sectors, require a proper definition of the incentives and technical training for promoting the adoption of proposed strategies to reduce GHG. Thus, future work is warranted to evaluate the proposed practices on different ecosystem services in the U.S. beef and dairy systems.

5. Conclusion

Progress toward the net-zero goal depends on the widespread adoption of appropriate mitigation strategies; policymakers and value-chain enterprises that have made commitments should pay close attention to the barriers to adoption, some of which are identified in this document. In addition, future research programs must prioritize identified research needs to promote wide adoption of the proposed strategies.

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Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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