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Review

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Special Issue
Applying Systems Thinking to Enhance Ecosystem Services

Edited by
Dr. Benjamin L. Turner, Dr. Erica Rieder and Dr. Hector Menendez

MDPI

https://doi.org/10.3390/systems12110446

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Applying Systems Thinking to Sustainable Beef Production Management: Modeling-Based Evidence for Enhancing Ecosystem Services

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Abstract: We used systems thinking (ST) to identify the critical components of beef cattle production through the lens of ecosystem services (ES), offering a holistic approach to address its adverse externalities. We identified eight critical feedback loops in beef production systems: (i) grazing and soil health, (ii) manure management and soil fertility, (iii) feed efficiency and meat production, (iv) water use and soil moisture, (v) cultural services and community engagement, (vi) energy use, (vii) carbon sequestration and climate regulation, and (viii) environmental impact. Our analysis reveals how these interconnected loops influence each other, demonstrating the complex nature of beef production systems. The dynamic hypothesis identified through the loops indicated that improved grazing and manure management practices enhance soil health, leading to better vegetation growth and cattle nutrition, which, in turn, have a positive impact on economic returns to producers and society, all of which encourage the continuation of interlinked beef and ecosystem stewardship practices. The management of beef production ES using ST might help cattle systems across the globe to contribute to 9 of the 17 different United Nations' Sustainable Development Goals, including the "zero hunger" and "climate action" goals. We discussed the evaluation framework for agrifood systems developed by the economics of ecosystems and biodiversity to illustrate how ST in beef cattle systems could be harnessed to simultaneously achieve the intended environmental, economic, social, and health impacts of beef cattle systems. Our analysis of the literature for modeling and empirical case studies indicates that ST can reveal hidden feedback loops and interactions overlooked by traditional practices, leading to more sustainable beef cattle production outcomes. ST offers a robust framework for enhancing ES in beef cattle production by recognizing the interconnectedness of ecological and agricultural systems, enabling policymakers and managers to develop more effective and sustainable strategies that ensure the long-term health and resilience of humans and ES.

Keywords: systemic perspective; sustainable beef agriculture; feedback loops; modeling; simulation

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Citation: Tedeschi, L.O.; Johnson, D.C.; Atzori, A.S.; Kaniyamattam, K.; Menendez, H.M., III. Applying Systems Thinking to Sustainable Beef Production Management: Modeling-Based Evidence for Enhancing Ecosystem Services. *Systems* **2024**, *12*, 446. https://doi.org/10.3390/systems12110446

Academic Editor: Wayne Wakeland

Received: 24 September 2024
Revised: 10 October 2024
Accepted: 21 October 2024
Published: 23 October 2024

1. Introduction

Systems thinking (ST) empowers us to grasp the intricacies of a system by examining its components, their interrelationships, and potential future behaviors, fostering a holistic understanding that encourages creative and bold approaches to system reformulation [1]. Applying an ST perspective to improve ecosystem services (ES), aiming to foster sustainable beef cattle production, involves a holistic approach to understanding and managing the complex interactions and inherent feedback within the whole beef cattle production chain from grazing to feedlot operations [2] and considering the feedback role of the beef sector on land use and food provisioning. Every optimally managed agricultural activity relies on ecosystem-based resources to produce a commodity while sustaining life on Earth through four different ES: provisioning, regulating, supporting, and cultural products and processes. However, these services become increasingly perturbed, distorted, or degraded when an agricultural system is managed with a reductionist mindset that tries solely to maximize productivity, thereby reducing productivity as well as exacerbating environmental impacts in the long term [3]. In beef cattle production, traditional management practices often fall short of their goals because of the unrecognized compensating feedback arising from the underlying complex structures that cross-cut domains. Thus, ST offers a universal approach to improving the health, quality, resilience, and management of ecosystem goods and services in beef cattle production, keeping in mind its holistic perspective for societal benefits [3].

Beef cattle production is an essential component of the agricultural system in certain areas covered by grasslands. Recent studies have further emphasized the importance of adopting ST and system dynamics (SD) to enhance the sustainability of beef production, highlighting the interconnectedness of environmental, economic, and social factors in achieving carbon neutrality and stewardship in agriculture, including proper natural resource management [4]. While often criticized for its environmental footprint, a comprehensive analysis must consider ST's impacts on ES, its potential benefits for food provisioning, and the unforeseen and unintended consequences that might arise in its absence [3,5]. The beef production footprint encompasses a range of ecological impacts, including elevated greenhouse gas (GHG) emissions, extensive land and water utilization, and significant effects on biodiversity related to life on land, life in the water, and life in the air [6,7].

The global demand for beef is projected to increase from 10.9 kg per person in 2020 for 8.1 billion people to 13.1 kg per person in 2050 for 10 billion people [8], indicating a significant growth in beef demand and thus requiring immediate attention with regard to its impact on ES. Recent studies have further emphasized the importance of adopting ST and SD to enhance the sustainability of beef production, highlighting the interconnectedness of environmental, economic, and social factors in achieving carbon neutrality and stewardship in agriculture, including proper natural resource management [4]. For instance, Capper et al. [9] analyzed the environmental and economic sustainability of adopting steroid implants within the Brazilian beef production system using a deterministic model based on cattle population demographics, nutrition, and performance. The study found that using steroid implants in cattle reduced resource use, GHG emissions, and economic production costs, thereby improving environmental and economic sustainability [9]. However, governmental regulations and social acceptability are issues that need to be addressed in the adoption of such technology.

The role of beef cattle production in climate change is complex and sometimes misunderstood. Well-managed grazing systems can aid soil carbon sequestration, a factor often ignored in climate change impact assessments [1,10]. While some studies argue that grazing cattle is unlikely to significantly increase soil carbon sequestration compared with land-use requirements and the associated emissions of beef production [11], others support strategies such as adaptive multi-paddock (AMP) grazing, which can sequester soil organic carbon at a rate of 3.59 Mg C ha^{-1} yr^{-1}. This can potentially reduce the GHG footprint of AMP grazing systems from 9.62 to 6.65 kg of carbon dioxide equivalent (CO_2eq) per kg of carcass when accounting for soil carbon sequestration [10]. The apparent contradiction in these findings stems mainly from variations in the initial state of grasslands and their management potential. The scope for further sustainability improvements may be limited when grasslands are already productive and well-managed. However, for degraded or overgrazed grasslands, implementing recovery strategies presents a promising avenue for the sustainable intensification of livestock production [12]. This nuanced understanding highlights the importance of context-specific assessments and tailored management approaches in optimizing the environmental impact of beef production systems.

When considering the environmental sustainability of beef production, it is crucial to note that the carbon footprint is just one of several factors, especially in rangelands, which offer a range of ecological goods and services, such as wildlife habitat, erosion control, water regulation, fire control, and cultural and esthetic benefits, which have not been thoroughly evaluated [13]. Tools such as life cycle assessment (LCA) and life cycle sustainability assessment (LCSA), supported by ST, can provide valuable frameworks for comprehensive sustainability analysis and decision-making [13–15]. LCA is an international organization-standardization-approved biophysical accounting framework used to compile an inventory of the material and energy inputs and output characteristics of each stage of a product life cycle and to quantify how these flows contribute to specified resource uses and emission-related environmental impact categories [16]. While these assessment tools provide valuable insights, it is important to consider the multifaceted nature of positive and negative impacts on beef cattle production for the ecosystem, wherein the relevance of ST-based production management lies.

Sustainable beef cattle (or any livestock, for the sake of inclusiveness) production encompasses not only environmental sustainability but also economic and social components [17]. The combination of variables that make a production system sustainable in one region may not work in another production situation because sustainability represents the state of a complex system that is constantly evolving [17]. It is essential to distinguish between sustainability and resilience: a sustainable system can coexist with other systems at a different output level after a period of perturbation, while resilience is the ability of a system to possibly recover and re-establish a dynamic equilibrium after it has been perturbed [17].

Emphasizing sustainable agroecosystems that promote culturally sensitive, economically viable, and socially fair farming systems can enhance beef production sustainability [18]. A comprehensive approach is needed to enhance sustainability in the meat production system. This approach includes digitalizing farming and livestock markets, enhancing nutrient use efficiency and recycling in feed production, integrating animal production with agroecology and industrial ecology principles, improving the health of individual animals and herds, and boosting animal health, production, and welfare by reducing stress during production. This approach can be used to develop and refine strategies to enhance ES in beef cattle production, ensuring that policies are robust and adaptable to changing conditions.

Scientists must ponder whether sustainability or resilience is the right approach for beef cattle production to face environmental challenges and to adapt to future climate and production conditions. Identifying the most efficient animals and feeding systems is a prerequisite to successful applications of sustainable livestock intensification programs [17]. This raises important questions: What defines efficiency in this context? Do truly energy-efficient animals exist, and how do we identify them? We must develop strategies that forecast the rate and magnitude of global changes as well as their possible influences on the food production chain, considering these complex considerations of animal efficiency and adaptability [17]. Nevertheless, another perplexing question is whether efficient animals in today's production systems are those that will be highly skilled at adapting when faced with future environmental constraints. Extensive rangelands offer yet further complexity in consideration of adaptable animals, as selecting production traits needs to include the ability to survive and reproduce in harsh environments with predator populations (e.g., olves).

The ST approach emerges as a powerful tool in this context because it accounts for the many variables and their interactions involved in identifying sustainable systems in each unique situation. Identifying stocks (e.g., cattle population, pasture biomass) and flows (e.g., births, deaths, feed consumption) is essential for modeling the dynamics of not only beef cattle production [1], but also of small ruminants [19], which can help in the iterative process of designing and testing policies in simulated environments [20]. This approach can help address the complex challenges of understanding systems and enhancing ES in beef cattle production while balancing environmental, economic, and social factors, ensuring that policies are robust and adaptable to changing conditions.

Objectives

This paper explores the application of ST to understand ES in beef cattle production, highlighting its potential to address current challenges and improve long-term sustainability. Specifically, we aimed to (1) identify and model critical components in beef cattle production that impact ecosystem services, considering their interconnectedness; (2) enhance ES by identifying feedback loops within beef production systems that influence sustainability outcomes, such as grazing, soil health, and manure management; (3) propose sustainable management strategies that can improve the environmental, economic, and social dimensions of beef cattle production, aligning them with the United Nations' Sustainable Development Goals (SDG); and (4) discuss the implications of these findings for policy-making and industry practices in the context of increasing global beef demand.

2. Systems Thinking Methodology and System Dynamics Modeling

2.1. Systems Thinking Methodology

ST is a holistic approach that emphasizes the understanding of interconnectedness and interdependencies within a system. Unlike traditional linear thinking, which focuses on isolated components and superficial cause-and-effect relationships, ST recognizes the importance of feedback loops, delays, and nonlinear relationships [21,22]. ST provides a conceptual framework for understanding the dynamics of integrated systems by focusing on dynamic complexity and feedback, developing dynamic hypotheses about behavioral origins, and modeling only the necessary system elements to explain specific phenomena [23]. The ST approach enables multi-scenario and multi-characteristic analyses as well as relative comparisons among several competitive management strategies over time [24]. Stocks, flows, and dynamic equilibrium are essential concepts in ST, where a stock represents the memory of changing flows within the system; if inflows exceed outflows, the stock level rises, whereas the opposite leads to a decrease, with dynamic equilibrium occurring when inflows equal outflows [1]. This approach acknowledges that human societies and economies are subsystems of the global ecosystem; thus, by applying ST, policymakers and managers can improve natural resource decision-making [25]. When applied to beef cattle production, ST can reveal hidden feedback loops and interactions that traditional practices may overlook, thereby leading to more sustainable outcomes.

2.2. System Dynamics Modeling

SD modeling is a valuable tool for applying ST to beef cattle production. SD modeling can be utilized in beef cattle production to apply ST by examining complex interactions and feedback loops, providing a holistic understanding of the system's structure and dynamics, simulating behavior, anticipating outcomes, and assessing the impacts of various management strategies [23,26]. These models simulate interactions within the system, help predict outcomes, and test different management strategies, enabling the testing of different management strategies and policies to assess their potential impacts on the system and allowing for informed decision making [23,26]. Jie et al. [27] described a simple SD model of the Australian beef supply chain, noting its potential benefits and challenges. Others discussed the use of SD for modeling animal agriculture systems at different scales and recommended increasing awareness and training in these methods [23]. Picanço Filho et al. [28] demonstrated the integration of SD with fuzzy cognitive mapping to assess sustainable development strategies, an approach that can be adapted for the beef sector. Mesgari et al. [24] propose an SD approach for solving complex problems in agricultural systems in Iran, enabling multi-scenario and multi-characteristic analyses under different policy conditions. Another study used SD modeling in rumen fill in an individual dairy cow and modeled the supply-chain-wide impacts of technology adoption by dairy farmers in Brazil [23]. The insights gained from these models support informed decision making and policy development and promote sustainable practices in beef cattle production.

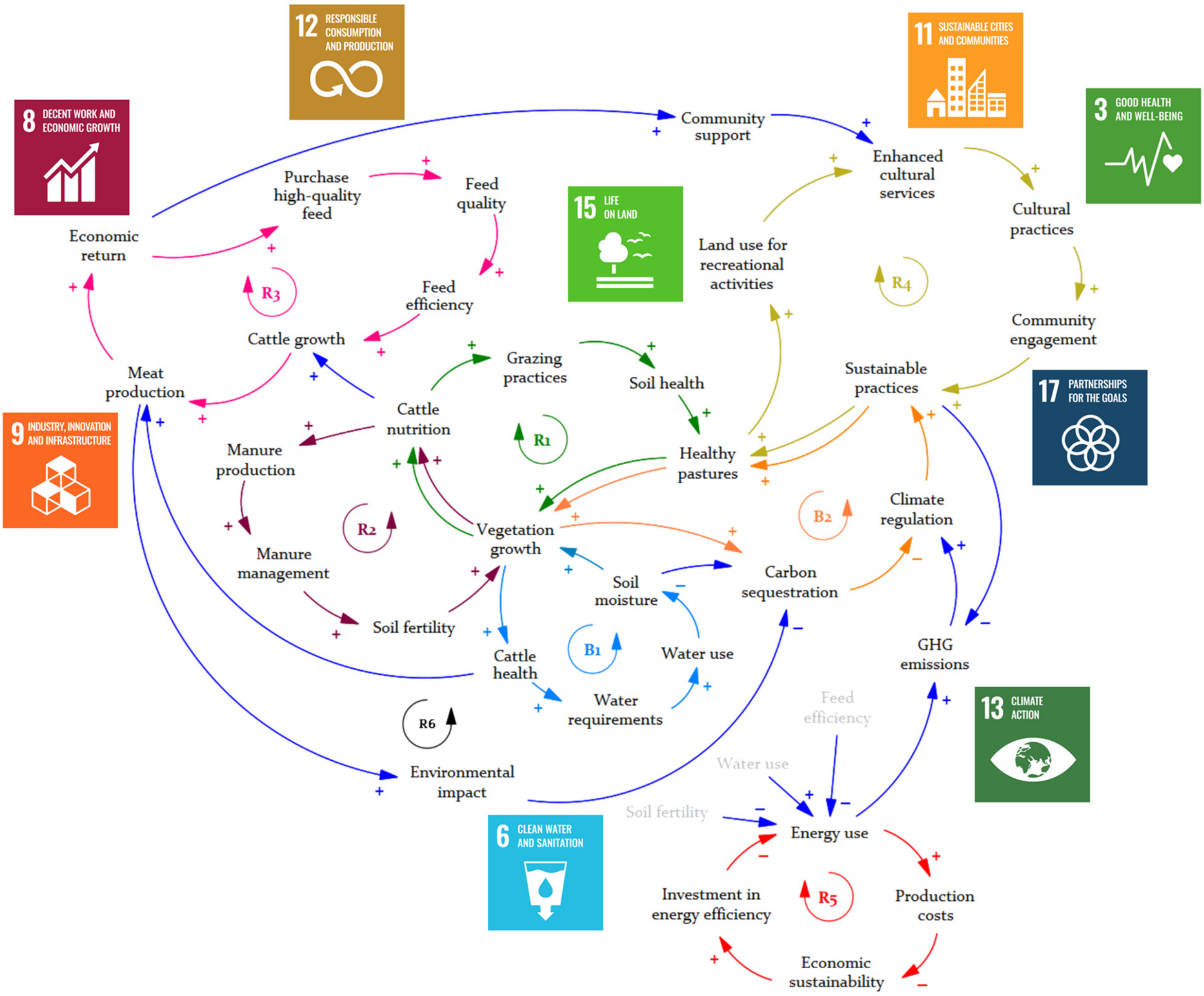
Integrating ST and SD into beef production strategies offers a pathway for effectively understanding and mitigating emissions while promoting a holistic approach to environmental stewardship [29]. ST allows us to recognize beef production systems' complex and interconnected nature, considering dynamic feedback loops and potential unintended consequences that can arise from narrowly focusing on optimizing certain aspects, such as productivity [30]. This approach enables a more comprehensive analysis of the entire production system from grazing management to supply chain operations, revealing opportunities for synergistic improvements that more traditional linear approaches may overlook. By embracing ST and SD, stakeholders can develop more resilient and sustainable beef production systems that balance productivity goals with environmental conservation and long-term ecosystem health. ST includes the use of highly communicative notation that allows one to read the dynamic interactions and the information flows through system variables. Feedback loops, as described by ST, are characterized by causal connections among variables (arrows) and a positive (+) or negative (−) sign indicating polarity, signifying a negative or positive correlation between two variables. A loop can be reinforcing (R; positive) or balancing (B; negative), depending on the algebraic product of the signs around the loops, which determines whether it is either positive or negative, respectively.

3. Understanding Ecosystem Services in Beef Cattle Production

Adopting sustainable practices and mitigating environmental impacts by using the entire ecosystem as a system boundary rather than just focusing on the livestock chain can ensure the long-term sustainability of beef cattle production. ES can be categorized as provisioning, regulating, supporting, or cultural services. In beef cattle production, provisioning services include meat and leather production; regulating services involve climate regulation, fire prevention, and water purification; supporting services encompass soil fertility and biodiversity; and cultural services are those that contribute to agricultural heritage and agrotourism [1,2]. However, mismanaged beef systems change the polarity of these services, thereby contributing to negative externalities, such as soil degradation, water scarcity, and GHG emissions. The environmental impact of beef cattle production is particularly concerning, as it contributes to deforestation, habitat loss, and an increased carbon footprint, especially in specific production systems where stocking rates exceed the regenerative biocapacity of the natural ecosystem. Addressing these challenges requires an ST approach to understand and manage the complex interactions within ecosystems and to plan future sustainable patterns of the ecosystem variables.

Beef production, particularly from cow–calf operations, contributes significantly to GHG emissions. For example, US beef cattle alone are responsible for 22.6% of the total agricultural emissions and approximately 2.2% of the total anthropogenic emissions of CO_2eq [3]. GHG emissions from beef production vary globally, with estimates from various sources placing the contribution of livestock to global anthropogenic GHG emissions at 7% to 18% [10]. The carbon footprint of beef cattle production varies, but methane (CH_4) emissions have been reported to account for 55% to 92% of the carbon footprint, with the majority of CH_4 arising from enteric fermentation [13]. However, these emissions could vary globally because of diverse production systems, which impact major environmental issues such as GHG emissions and resource efficiency [31]. The most common solutions used by beef systems across the globe to counter the above impacts include the use of conventional productivity-enhancing technologies [32], genotypes suited to environmental variation [33], and the availability of ES [34]. Among other countries, it has been reported that the USA, New Zealand, Uruguay, the United Kingdom, and Australia have a footprint of less than 1 kg of CO_2eq per kilogram of fat- and protein-corrected milk [35]. Therefore, reducing GHG emissions from the specialist grazing livestock sector could substantially lower the climate impact of the entire agricultural sector. The best management practices in grazing systems could reduce enteric CH_4 emissions by as much as 22% compared with continuous grazing [16].

Combining ST and SD to understand the critical aspects that can enhance ES in beef cattle production is essential for achieving the sustainability goals of this agricultural activity. Figure 1 highlights eight feedback loops relevant to beef cattle production systems worldwide, and Table 1 lists 19 real-world modeling studies that support these eight feedback loops.



Feedback Loop	Targeted Sustainable Development Goals (SDGs)
Grazing and Soil Health (R1)	SDG 2: Zero Hunger, SDG 13: Climate Action, SDG 15: Life on Land
Manure Management and Soil Fertility (R2)	SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 15: Life on Land,
Feed Efficiency and Meat Production (R3)	SDG 2: Zero Hunger, SDG 12: Responsible Consumption and Production, SDG 13: Climate Action
Cultural Services and Community Engagement (R4)	SDG 4: Quality Education, SDG 8: Decent Work and Economic Growth, SDG 11: Sustainable Cities and Communities
Energy Use (R5)	SDG 7: Affordable and Clean Energy, SDG 13: Climate Action, SDG 12: Responsible Consumption and Production
Meat Production and Environmental Impact (R6)	SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 15: Life on Land
Water Use and Soil Moisture (B1)	SDG 6: Clean Water and Sanitation, SDG 13: Climate Action, SDG 15: Life on Land
Carbon Sequestration Loop (B2)	SDG 12: Responsible Consumption and Production, SDG 13: Climate Action, SDG 15: Life on Land

Figure 1. The schematic representation of eight primary feedback loops of the ecosystem services affected by typical beef cattle production and their relationship with potential United Nations' Sustainable Development Goals (SDG). The reinforcing loops (R) amplify changes in the system. When an element in the loop changes, the loop causes further changes in the same direction, leading to exponential growth or decline. The balancing loops (B) counteract changes in the system. When an element in the loop changes, the loop causes adjustments that bring the system back toward a stable state or equilibrium. The plus (+) and minus (−) signs are used to indicate the nature of the relationship between the variables: plus indicates reinforcing or amplifying relationships, and minus

indicates balancing or counteracting relationships compared with the original (previous) state of the variables. The SDG icons are from https://www.un.org/sustainabledevelopment/news/communications-material (accessed on 20 October 2024).

3.1. Grazing and Soil Health Loop

The grazing and soil health loop (R1) in Figure 1 represents a reinforcing cycle where better grazing practices lead to improved soil health. Practices such as regenerative and rotational grazing enhance vegetation growth, subsequently improving cattle nutrition. This positive impact encourages the continuation of these beneficial grazing practices, creating a sustainable cycle.

Improved soil composition plays a significant role in this loop. For instance, a study in the plains of Vichada focused on enhancing cattle food nutrition and livestock productivity by improving soil composition and treating soil acidity with mineral amendments. The study found that the proposed radial module not only acts as an efficient carbon sink, capturing twice the emissions produced by cattle, but also improves soil quality. It generates 500 tons of humus, 1666 tons of organic fertilizer, and 71,400 m^3 of biogas annually for bioenergy utilization [36]. Furthermore, inter-seeding low-quality forage rangelands with nitrogen-fixing legumes can enhance production and soil quality, aid carbon sequestration, and maintain legume populations through virtual fencing technologies that optimize grazing patterns and soil health alongside targeted grazing and prescribed burning techniques to control invasive species and promote native vegetation [37].

Enhanced soil health is another crucial benefit of improved grazing practices. Management-intensive rotational grazing in subhumid cool-season pastures has shown positive effects on biomass production, increasing both forage quantity and quality [22,38]. Although it reduces fine-root production, this method significantly improves the overall forage production and quality compared with continuous grazing and haymaking [22]. Moreover, management-intensive grazing (MiG) has been shown to improve chemical and biological soil health indices over time [39]. The AMP grazing approach (Table 1) can also reduce greenhouse gas emissions due to high soil-carbon sequestration rates [10]. Compared with single pastures, the reinforcing action (R1) will likely accelerate as these practices are adopted across watershed-level areas, as pasture areas are interdependent on the surrounding areas.

Table 1. The collection of real-world and modeling studies is used as supportive evidence for each of the eight primary loops identified by our system-dynamics-based causal-loop diagram shown in Figure 1.

Loop	Authors	Real-World Example	Model/Methodology
Grazing and soil health	[40]	Pastoralism in the Silesian Beskid Mountains, focusing on biodiversity in fresh meadows and Nardus grasslands. Grazing positively impacts the maintenance of vegetation, including in EU-protected habitats. Dairy is the most popular provisional service, while not all potential ecosystem services are realized.	Spearman rank correlation, ANOVA, non-metrical multidimensional scaling (NMDS) with Bray–Curtis distance
	[10]	AMP grazing reduced net GHG emissions to 6.65 kg CO_2eq kg^{-1} carcass weight due to high soil-carbon sequestration rates. Feedlot finishing had net GHG emissions of 6.12 kg CO_2eq per kg carcass weight. The study challenges the assumption that only feedlot intensification reduces the overall beef GHG footprint.	Life cycle assessment (LCA) and soil carbon accounting

Table 1. *Cont.*

Loop	Authors	Real-World Example	Model/Methodology
	[39]	Management-intensive grazing (MiG) in pivot-irrigated perennial pasture systems. MiG improved chemical and biological soil health indices over time. Physical soil health index decreased due to increased bulk density from cattle hoof pressure. Soil organic carbon remained unchanged, but increases in microbial and enzymatic activities suggest potential future SOC increases.	Soil management assessment framework (SMAF)
Manure management and soil fertility	[16]	Comparison of beef production strategies in the Upper Midwestern United States. Feedlot-finished beef has the lowest environmental impacts across all categories, while pasture-finished beef has the highest. Sensitivity analyses suggest that pasture systems could reduce greenhouse gas emissions if soil organic carbon sequestration is positive. The cow–calf phase is the most resource- and emissions-intensive part of beef production.	Excel-based manure nutrient and solids excretion estimator, IPCC Tier 1 emission factors, life cycle assessment (LCA)
	[36]	The rational rotational regenerative grazing system was used, and the proposed radial module was shown to be a very efficient carbon sink system that is able to capture twice the amount of equivalent emissions that cattle emit. It organically improves soil quality and produces 500 tons of hummus, 1666 tons of organic fertilizer, and 71,400 m^3 of biogas per year for bioenergy utilization. The project safeguards forests, protects biodiversity by forming ecological corridors, and optimizes water management.	Anaerobic digesters, vermicomposting, and radial module designs for carbon sequestration
Feed efficiency and meat production	[17]	Focused on genetic potential and nutrient use efficiency in beef production systems. Sustainable intensification is essential for increasing food production while reducing the environmental impact. Identifying efficient animals and feeding systems is crucial for successful sustainable livestock intensification.	Computerized mathematical model, CNCPS (Cornell Net Carbohydrate and Protein System)
	[27]	Beef supply-chain simulation from cattle arrival to carcass processing. The model explores the impact of policy choices on key performance indicators such as quality, responsiveness, and efficiency. Responsive strategies have a limited impact on labor costs but significantly affect process capacity requirements and fixed costs.	Vensim model for system dynamics
	[41]	Intensive feed-bunk management systems, such as slick-bunk management. The study found that programmed feeding strategies, including both programmed gain and restricted feeding, resulted in greater observed average daily gain than predicted, improved feed efficiency, and decreased total feed consumption to reach equivalent harvest endpoints. Additionally, managed feeding approaches that eliminated extreme swings in feed intake decreased overall feed intake by 12% compared with ad libitum feeding while improving gain efficiency without affecting average daily gain or carcass weight.	Simulation tools for feed management. The simulations focused on two scenarios: the use of programmed feeding as an alternative to traditional high-forage growing programs before a feedlot finishing period and the use of programmed feeding for a portion of the feedlot finishing period.
Water use and soil moisture	[4]	Example of soil erosion prediction in the Alqueva dam watershed in Portugal. Common attempts to alleviate (agriculture and natural resource management) problems have suffered from a reliance on short-term management strategies. Longer-term thinking and strategies aimed at fundamental solutions are needed to address AGNR problems effectively. System dynamics (SD) should be a central tool for conducting transdisciplinary research to address complex AGNR issues.	Revised Universal Soil Loss Equation (RUSLE)

Table 1. *Cont.*

Loop	Authors	Real-World Example	Model/Methodology
	[42]	Assessment of land-use/cover changes on the earth system. The paper discusses the dynamics of land cover and land use as a coupled human–environment system; the advances in observation, monitoring, and land characterization; and the challenges remaining in LCS (land-change science) research.	Land-use change models: IMAGE (Integrated Model to Assess the Global Environment), CLUE (Conversion of Land-Use Change and its Effects), and SALU (Sahelian Land Use). These models are used to assess and project the future role of land-use/cover changes in the functioning of the earth system and to gain insights into land systems from various perspectives.
Cultural services and community engagement	[43]	Globally important agricultural heritage system practices are influenced by a top-down approach that prioritizes government authority discourses over local narratives. Tourism development has not incentivized locals to continue farming, and many feel excluded from decision-making processes.	An empirical case study approach focuses on Baohua Town and the Samaba Rice Terraces. Three field trips over 2017–2018, spending a total of six months visiting four villages near the Samaba Rice Terraces.
	[12]	Optimized pasture management strategies significantly increase net present values compared with traditional practices. Emissions intensity is substantially reduced through optimized pasture management, with further reductions achieved by accessing subsidized credit to the communities. Optimized pasture management practices can double or triple beef production while significantly reducing greenhouse gas emissions.	The study developed a multi-period linear programming model to optimize pasture management decisions for a typical beef cattle farm in the Brazilian Cerrado.
	[40]	Cultural resurgence in the Silesian Beskids related to traditional shepherding practices	Analysis of cultural services and community engagement
Energy use	[18]	Feed conversion ratio (kg food consumed to kg gain in liveweight or product), or the energy efficiency of the individual animal (MJ feed energy consumed to MJ energy produced)	The feed conversion ratio is a better indicator of efficiency than average daily weight gain, and residual feed intake is a heritable trait independent of body size, sex, and age, involving a comparison of metabolic body weight and average daily gain.
	[27]	Simulation of cattle processing interactions affecting energy use	Vensim model for system dynamics
Carbon sequestration loop	[8]	Demand and supply dynamics of livestock-derived foods impacting carbon sequestration. The study underscores the importance of interactions between income, prices, and the income elasticity of demand in projecting future livestock-derived food demand.	International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)
	[18]	Impact of land-use changes on carbon sequestration. Improving nutrient use efficiency, recycling in feed and animal production, biosecurity measures, selective breeding, and mitigating animal stress are crucial elements for sustainable meat production.	Life cycle assessment

Table 1. *Cont.*

Loop	Authors	Real-World Example	Model/Methodology
	[19]	Analysis of climate change impacts and alternative production scenarios. Simulation modeling, particularly system dynamics, can enhance financial returns and reduce negative environmental impacts in small-ruminant production.	System dynamics models
Meat production and environmental impact	[15,31]	Evaluation of the environmental performance of beef production. Beef production has significant environmental impacts, particularly in terms of global warming potential, acidification potential, eutrophication potential, land use, and water depletion.	Life cycle assessment
	[6]	Simulation of hypothetical farms to assess production efficiency and environmental impacts. The study found low farm self-sufficiency, with most farms being dependent on purchased concentrates, but high forage self-sufficiency	Farm-model studies
	[9]	Assessment of regional variations in greenhouse gas emissions from beef production. Steroid implants in Brazilian beef cattle reduce resource use, GHG emissions, and economic costs, thereby improving sustainability. Implants improve feed conversion efficiency, average daily gain, and carcass weights, reducing the number of cattle and time needed for production. Economic benefits include increased beef production, reduced costs, and higher returns on investment.	Carbon footprint analysis

Increased soil carbon sequestration is another advantage of improved grazing practices. Grazing beef cattle can enhance soil carbon levels through effective grass management strategies, such as rotational grazing systems, establishing pastures on depleted lands, and optimizing grazing management to boost the nutritional quality and herbage availability [3]. These practices benefit the environment and contribute to the long-term sustainability of the grazing system.

Reduced GHG emissions can be achieved by adopting best-management practices in grazing systems, potentially lowering enteric CH_4 emissions by up to 22% compared with continuous grazing [16]. Managing livestock distribution and grazing timing improves plant community dynamics in subhumid grasslands, enhancing forage production and quality [22]. This management strategy also leads to increased nutrient cycling, as the livestock consumption of plant residues boosts nutrient cycling rates, benefiting crop production, including cover crops and annual forages [37]. Grazing positively impacts the maintenance of vegetation [40] and contributes to the spatial heterogeneity of vegetation based on the interaction between grazing patterns and pre-existing vegetation patterns [44].

Finally, improved soil health parameters have been observed with agroforestry and grass-buffer effects on soil health in grazed pasture and row-crop systems. These practices indicate the potential for improved grazing to impact soil health positively (Table 1) [39]. By implementing these strategies, farmers and ranchers can create a more sustainable and resilient grazing system that benefits both the environment and their livestock.

3.2. Manure Management and Soil Fertility Loop

The manure management and soil fertility loop (R2) in Figure 1 is also a reinforcing cycle whereby effective manure management enhances soil fertility, which, in turn, promotes better vegetation growth and improved cattle nutrition. This positive feedback loop is driven by the recycling of nutrients back into the soil, reducing the need for synthetic fertilizers and improving soil health. For example, effective manure management, such as composting the manure before application [10], enhances soil fertility for improved vegetation growth, which leads to better cattle nutrition in grazing systems such as no-till farming [45]. This results in more manure production, which, if managed well, further enhances soil fertility. Manure collected from feedlots and applied to agricultural land can significantly reduce the need for synthetic nitrogen inputs by 31.4%, thereby lowering the carbon footprint associated with fertilizer production [10]. Additionally, the application of managed livestock manure contributes to increased soil organic carbon, promoting carbon sequestration and enhancing soil organic carbon and nitrogen stocks [3].

CH_4 from enteric fermentation is the predominant source of emissions in pasture-based systems, while manure management and feed production are significant in more intensive systems [35]. In semi-arid regions like West Africa, strategies such as night corralling and crop–livestock integration are employed to ensure that the manure reaches the fields, enhancing soil fertility despite constraints like inadequate forage and animal diseases. In Madagascar, for instance, converting manure to biogas is considered a superior option, as it provides alternative energy sources and reduces the negative health impacts of traditional cooking methods [46].

Forage legumes also improve soil health by increasing the presence of microorganisms (Table 1) that enhance nutrient cycling and maintain nitrogen availability for plant uptake [16]. Furthermore, using slow-release fertilizers like coated urea and nitrification inhibitors can reduce nitrogen losses through ammonia volatilization and nitrous oxide emissions, thereby increasing nitrogen use efficiency in forage plants [47].

Alternative methods to composting manure (e.g., scraping and spreading) involve collecting manure from feedlots and applying it to nearby agricultural land within a 5 km radius. These practices, along with the use of urease and nitrification inhibitors, can further reduce GHG emissions and improve nutrient retention in the soil [47]. Other sustainable manure management practices include anaerobic digesters, vermicomposting, and radial module designs for carbon sequestration [36].

Chemical fertilizers and carbon dioxide emissions can be avoided using sustainable products such as black soldier fly larvae, which can be given as a feed substitute. The production of one kg of dried larvae emits 3.1 kg CO_2eq, while it prevents 9.7 kg CO_2eq. Moreover, chemical fertilizers can be avoided by using black soldier fly larvae manure as an organic fertilizer [7]. This innovative approach not only reduces greenhouse gas emissions but also provides a valuable source of nutrients for soil fertility improvement.

3.3. Feed Efficiency and Meat Production Loop

The feed efficiency and meat production loop (R3) in Figure 1 is also a reinforcing cycle whereby improved feed quality enhances feed efficiency, leading to better cattle growth and health and, ultimately, resulting in higher meat production. This positive feedback loop is driven by optimal feeding strategies and integrated livestock systems, which not only improve production but also contribute to environmental sustainability.

Optimal feeding strategies, such as slick-bunk management and programmed feeding, play a crucial role in this loop. Slick-bunk management involves time-based restrictions to limit daily variations in feed delivery, reducing the overall feed intake and CH_4 emissions. Programmed feeding, on the other hand, decreases the overall feed intake, further lowering CH_4 (Table 1) emissions and nutrient excretion and enhancing the feed efficiency and overall gain [41]. These strategies not only improve animal performance but also contribute to reducing the environmental impact of livestock production.

Improved feed quality has a significant impact on reducing greenhouse gas emissions and boosting production efficiency [48]. For instance, a study found that enhancing feed quality reduced enteric CH_4 production by 20% across seven different feed scenarios [38]. Farmers can optimize nutrient utilization and minimize waste by providing high-quality feed, leading to more sustainable meat production.

Integrating livestock into farming systems can enhance soil health and vegetation growth while improving cattle nutrition and overall production efficiency. These integrated systems, particularly zero grazing, confine cattle and provide all their feed, leading to higher feed efficiency and reduced land use compared with traditional grazing systems. This approach is crucial as beef production requires significantly more land than crop production per 100 g of protein. Shifting to more efficient systems can reduce carbon emissions from direct agricultural production by over 60% [11]. Moreover, intensive systems, including zero grazing, can enhance soil health (Table 1) by reducing the pressure on land resources and promoting better nutrient management [20,27].

Sustainable intensification is crucial for increasing food production with minimal environmental impact, and successful sustainable livestock intensification hinges on identifying efficient animals and feeding systems (Table 1) to enhance feed efficiency, thereby improving the output-per-input ratio and reducing greenhouse gas emissions [17]. By focusing on efficiency and sustainability, farmers can optimize their production systems while minimizing their environmental footprint.

Economic returns from better production incentivize further investment in feed quality. Intensive systems have been shown to more than double beef and dairy production over the past few decades, despite a reduction in the total number of pure-bred cattle being raised globally, leading to higher profit margins due to lowered production costs and increased efficiency [49]. This economic incentive drives farmers to continually improve their feeding strategies and to invest in sustainable practices.

However, treating livestock merely as production machines has caused significant environmental and ethical issues. To address these concerns, adopting novel tools like digitalization, precision livestock farming, and artificial intelligence, along with improving nutrient use efficiency, recycling, biosecurity measures, selective breeding, and stress mitigation, can significantly enhance sustainability in meat production [18].

3.4. Water Use and Soil Moisture Loop

Unlike previous feedback loops, the water use and soil moisture loop (B1) in Figure 1 is a balancing loop, because increased water use meets the cattle's higher water requirements but can also reduce the soil moisture. Reduced soil moisture can negatively impact vegetation growth, which, in turn, may affect cattle health, creating a need to balance water use efficiently. Healthy cattle have higher metabolic rates and require more water to support their bodily functions, including digestion, temperature regulation, and milk production. Conversely, unhealthy cattle may consume less water due to decreased appetite or illness. Increased water usage can reduce the amount of water available in the soil, particularly if water is drawn from local sources like rivers and wells that also contribute to soil moisture.

Many countries, particularly in regions spanning from China through India and Pakistan to the Middle East and North Africa, currently, or soon will, fail to have adequate water to maintain their per capita food production from irrigated land. Roughly 20% of the irrigated area in the United States is supplied by groundwater pumped in excess of recharge, with overpumping also a severe concern in China, India, and Bangladesh [50]. Inefficiencies in water distribution mean that a significant portion of water is lost before crops can utilize it. Only 40% to 50% of irrigation water is effectively used in crop growth, leading to reduced soil water availability [51].

Efficient water management practices can mitigate this by ensuring that water usage for cattle is balanced by maintaining soil moisture levels through irrigation practices that support both cattle and pasture needs. Strategies such as rainwater harvesting, in situ micro-catchment techniques, and small-scale irrigation can help improve water availability and soil moisture retention in beef cattle production systems, which ultimately benefit cattle health and vegetation growth [46]. Incorporating soil health management practices that enhance infiltration and prevent runoff during extreme precipitation events can help maintain soil moisture levels for cattle and pasture needs [37]. Optimizing water management not only benefits cattle and vegetation but also reduces the energy consumption associated with pumping, transporting, or treating water, aligning with the United Nations' Sustainable Development Goals [36].

For example, one intervention that involved converting an irrigated cropland area into a MiG system for cattle resulted in grazing cow–calf pairs, replacement heifers, and steers on irrigated pastures with permanent infrastructure like fencing and water access points. Cattle were frequently moved to new paddocks every 1 to 3 days based on forage availability, targeting 50% utilization of the available forage during each grazing period. Over time, this MiG system improved the chemical and biological soil health indices, although physical soil health decreased due to the increased bulk density from cattle hoof pressure. Soil organic carbon remained unchanged, but increases in microbial and enzymatic activities suggest potential future increases in soil organic carbon [39].

Innovative practices like Zai pits in Burkina Faso, Mali, and Niger have demonstrated improved crop yields and water infiltration, aiding sustainable agriculture [46]. Practices like ultra-high-stock-density grazing and the cattle–majada concept can enhance soil fertility by incorporating manure and urine into the soil, thereby improving its water retention capacity. Implementing keyline design for water management, which involves creating iso-lines for rainwater management and using hydraulic pumps to transport water, can improve water infiltration and availability for both crops and livestock [36].

Using mechanical methods to incorporate manure and urine into the soil while preserving its integrity through "soft plowing" can enhance soil moisture retention and improve overall soil health [51]. Furthermore, integrating trees into cropping systems, known as agroforestry, can improve the nutrient availability and efficiency of use, reduce erosion, and provide additional benefits, such as firewood and carbon storage [50,52].

Improving the water and nutrient efficiency of agriculture by targeting specific "hotspots" of low efficiency, where a disproportionate use of inputs relative to production occurs, and deploying agroecological innovations in crop and soil management, along with precision agriculture, drip irrigation, organic soil remedies, and wetland restoration, can significantly reduce water use and pollution [53]. Land-use models (Table 1) can be analyzed to provide insights on water utility in the region [42], helping to optimize water management strategies for sustainable cattle production and soil health. Utilizing the ST and SD approach to capture these complex water management and sustainability challenges is critical for determining systemic and scalable interventions across cattle production areas and phases. Menendez et al. [54] created a dynamic water-footprint model that conceptualizes the reinforcing and balancing loops that impact individual, herd, ranch, and production phases (e.g., cow–calf, background/stocker, and feedlot). This conceptualization helps unpack the complexities behind meat production, nutrient use efficiency, and policy at large regional scales using the systems approach. Further, Menendez and Tedeschi [55] operationalized this dynamic water-footprint model to compare it with the original water-footprint accounting methods developed in 2002 [56] by the Delft Institute For Water Education and, more recently, by the International Organization for Standardization and the Food and Agriculture Organization of the United Nations by capturing various spatial, climatic, temporal, and animal functions (water-use changes due to animal physiology (rumen function, growth) and environment), and nutritional feed inputs (hay, pasture, concentrates). This model allows any combination or intervention to be tested within and across supply chains and regions with various functional units (e.g., liters per kg of boneless beef). For example, Atzori et al. [57] have suggested different coefficients such as the net water footprint, which accounts for different levels of water-use efficiency, resulting in differences ranging from 4% to 63% compared with conventional water-use evaluation methods. This robust tool ultimately helps policy and decision makers to quantify the intended and unintended consequences of blue, green, and gray water use for water-use and water-footprint estimation.

3.5. Cultural Services and Community Engagement Loop

The cultural services and community engagement loop (R4) in Figure 1 is another reinforcing loop because promoting agrotourism and educational initiatives fosters community involvement, leading to the integration of cultural heritage into practices and enhancing sustainability efforts. Community engagement leads to the adoption of sustainable practices (e.g., agroforestry and rotational grazing) that lead to improved vegetation growth (e.g., better soil management and reduced overgrazing). It also fosters a sense of ownership and responsibility among community members, leading to increased compliance and participation in sustainable agricultural initiatives [58].

Agricultural heritage systems should be viewed as dynamic, living systems rather than static cultural relics. Conservation efforts need to incorporate human knowledge and action as integral parts of these systems. The concept of "dynamic conservation" and the framework of extended coevolution are essential for understanding and preserving these systems [59]. This is exemplified by the Globally Important Agricultural Heritage Systems (Table 1), which emphasizes the dynamic conservation and adaptive management of agricultural landscapes, ensuring that local knowledge and practices are preserved and utilized sustainably [43].

Increasing awareness and appreciation of traditional farming practices and sustainable agriculture among visitors and local communities provides opportunities for direct engagement with beef cattle production systems, encourages the adoption of environmentally friendly practices, creates economic opportunities through agrotourism, and strengthens community ties by connecting consumers with producers, thereby fostering stewardship toward the land and livestock and promoting sustainable consumption patterns [48].

In regions like Pamekasan Regency, the socio-cultural aspects, including financial security, income, and social status, play a crucial role in supporting sustainable beef cattle farms. Farmers' motivations (e.g., saving for large expenditures and cultural events) drive the adoption of new technologies and improved management practices, leading to increased productivity and income [60]. Promoting agrotourism and community engagement can significantly enhance sustainability in beef cattle production by integrating sustainable practices and cultural heritage. Agrotourism provides economic incentives for local communities, encouraging them to adopt and maintain sustainable agricultural practices. For instance, the integration of legumes into grass pastures, a practice increasingly adopted due to high fertilizer prices, enhances forage production, animal weight gain, and nutrient cycling, thereby reducing the reliance on chemical fertilizers and irrigation, which, in turn, lowers greenhouse gas emissions [47].

Sustainable agriculture requires increased knowledge-intensive technologies for decision-making at the field level, the active exchange of information among scientists and farmers, and global investments in technology and human resources to ensure sustainability [50]. A study developed a multi-period linear programming model to optimize pasture management decisions for a typical beef cattle farm in the Brazilian Cerrado. The model simulates beef production, accounting for herd dynamics, financial resources, feed budgeting, pasture recovery dynamics, and soil carbon stocks. The model optimizes pasture management decisions to maximize profit, subject to biological and financial constraints. Optimized pasture management strategies significantly increase net present values compared with traditional practices, and the emissions intensity was substantially reduced through optimized pasture management, with further reductions achieved by accessing subsidized credit. Optimized pasture management practices (Table 1) can double or triple beef production while significantly reducing greenhouse gas emissions [12].

Given the high productivity of these pastures, more land becomes available for enhanced cultural services (e.g., improved landscapes for recreation and educational opportunities), leading to increased community engagement. It can also enhance cultural services and community engagement by providing opportunities for community members to engage in traditional practices, fostering a sense of cultural identity and connection to the land [52]. However, as seen in the empirical case study of Baohua Town and the Samaba Rice Terraces, most residents are excluded from local heritage practices, leading to potential emigration and depopulation. Globally Important Agricultural Heritage Systems practices are influenced by a top-down approach that prioritizes government authority discourses over local narratives. Tourism development has not incentivized locals to continue farming, and many feel excluded from the decision-making processes [43].

If pastures are further degraded because of overgrazing and other practices with unintended negative environmental consequences, less land is available for ES that involve cultural services, leading to a negative perception of agricultural production; explicitly, grazing beef cattle systems. Similarly, it highlights the connection between the community and animal production sectors.

Community engagement will increase the adoption of animal welfare practices (e.g., better nutrition and humane handling) that should improve animal health and production, leading to higher quality outputs (meat and dairy) and increased economic viability that could spark further community support and enhance cultural services, making the community further engaged [61]. Community involvement in sustainable practices can improve animal welfare and economic viability in beef cattle systems by promoting the adoption of practices that prioritize animal health and well-being, leading to improved productivity and economic returns [18]. For example, pastoralism in the Silesian Beskid Mountains not only provides ES and cultural heritage, but sheep grazing also enhances biodiversity, supports cultural tourism, and contributes to the community by providing meat, dairy, wool, and cultural value. The grazing of sheep of different breeds on pastures in the Silesian Beskid mountains during the vegetation season positively impacts the maintenance of vegetation, including European Union-protected habitats. Dairy is the most popular provisional service, while not all potential ES are realized. The cultural heritage of pastoralism (Table 1) significantly enhances the touristic attractiveness of the Silesian Beskid region [40].

Community engagement can provide opportunities for knowledge sharing and the development of innovative solutions that benefit both animals and the community's economic interests [37]. Climate-smart livestock practices are context-specific and require stakeholder consultation. Investment in infrastructure and policy support is crucial for the success of climate-smart agriculture (CSA) [46]. A holistic approach focusing on organic production, renewable energy, landscape conservation, and diverse product offerings is proposed as the best strategy for sustainable and economically viable wine tourism, as seen in the "Azienda Agricola Model" for sustainable enotourism (i.e., wine tourism centered around the appreciation and enjoyment of wine) and eco-enotourism at the micro-regional level [62].

3.6. Energy-Use Loop

The energy-use loop (R5) in Figure 1 is deemed a reinforcing loop because increased water use typically requires more energy for pumping and transport, thus increasing production costs. Investment in energy efficiency can reduce energy use and costs, but the initial relationship tends to reinforce the increased energy consumption with higher water usage. The energy-use loop is directly connected to the other loops.

Increased soil fertility reduces energy use. Sustainable grazing practices improve soil health and vegetation growth, reducing the need for external inputs such as fertilizers and pesticides, which lower energy consumption. Effective manure management, such as composting, can contribute to soil fertility and reduce the need for energy-intensive synthetic fertilizers [48]. Improved soil fertility can enhance water retention and reduce the need for irrigation, thereby reducing the energy use associated with water management in agriculture [50]. Sustainable grazing practices, such as AMP grazing [10], MiG [39], and effective manure management using techniques such as radial module designs, which capture double the carbon emissions of cattle and enhance soil quality while producing hummus, biofertilizer, and biogas for energy [36]; increase soil fertility and vegetation growth; and reduce the reliance on energy-intensive external inputs, promoting overall agricultural sustainability.

By adopting practices such as crop rotation, reduced tillage, and the use of organic matter, soil fertility can be restored and maintained, thereby reducing the need for energy-intensive inputs like chemical fertilizers and irrigation systems [50,63]. For instance, conservation agriculture, which includes minimum soil disturbance, permanent organic soil cover, and crop rotations, has been shown to enhance soil health and fertility while maintaining or improving crop yields. This approach reduces the energy required for tillage and the production and application of synthetic fertilizers [63]. However, changes in the albedo of soil (high residue vs. dark soils) alter planting dates (growing degree days) and may cause excessive moisture, so these management practices are not without unintended feedback in some instances. Additionally, technologies such as drip and pivot irrigation can improve water-use efficiency and decrease salinization, further reducing the energy needed for water pumping and distribution [50]. The integration of sustainable practices, such as the use of cover crops and organic amendments, can further enhance soil organic matter, leading to improved soil structure, water-holding capacity, and reduced erosion. This not only conserves energy but also mitigates environmental impacts such as eutrophication and greenhouse gas emissions from agricultural runoff and manure management [16,53].

Modifying grazing management to match forage supply with demand, reducing heat stress, and improving livestock production, along with strategic use of protein and energy supplements and grazing cover crops during typical forage-use periods, can significantly enhance grazing land management [37]. Feed conversion efficiency is a critical metric, as a 10% improvement can lead to a 43% increase in profit, making it a more reliable indicator of efficiency than average daily weight gain. By targeting low residual feed intake, which is a heritable trait independent of body size, sex, and age, farmers can enhance feed efficiency, thereby reducing the amount of feed (Table 1) required per unit of meat produced [18]. Precision feeding systems can lead to the decreased production of manure and simplified feed-bunk management, which can contribute to reduced energy consumption. Programmed and restricted feeding strategies have shown promise in decreasing the overall feed intake and increasing the gain efficiency, which, in turn, reduces enteric CH_4 emissions and nitrogen excretion. These feeding strategies can replace traditional high-forage diets with high-grain diets, further decreasing CH_4 emissions due to lower dry matter intake and increased starch concentration in the diet [41].

Intensive farming systems, which often rely on high stocking rates and purchased concentrates, can also benefit from improved feed efficiency by reducing the global warming potential associated with poor efficiency performances. Enhancing farm self-sufficiency through the use of on-farm-grown grains and efficient cropping systems, such as those based on legume crops and silage conservation, can further reduce energy consumption and environmental impacts [6]. Additionally, incorporating ES into the evaluation of beef production systems can markedly reduce environmental impacts (including the global warming potential, acidification potential, and eutrophication potential) by leveraging natural pastures and biodiversity conservation [34]. Optimized pasture restoration can inform the economics of restoration targets and suggest significantly increased profitability and reduced emissions through strategic partitioned pasture restoration [12].

Furthermore, sustainable grazing practices and effective manure management contribute to carbon sequestration in the soil, which can help mitigate GHG emissions and reduce the carbon footprint of agricultural systems [10,18]. Thus, enhanced soil health and vegetation reduce soil erosion and increase productivity, thereby contributing to overall sustainability. Implementing best management practices such as no-tillage farming, cover cropping, biochar application, and agroforestry can increase soil organic carbon stocks, thereby reducing the energy required for soil preparation and maintenance [48,64]. Additionally, converting marginal agricultural lands to woodlands or incorporating perennial grasses can act as permanent carbon sinks, reducing the need for frequent replanting and associated energy costs [48]. Integrating livestock with crop production, as seen in agrosilvopastoral systems, can further optimize carbon sequestration while reducing CH_4 emissions from ruminants and improving nutrient cycling, which decreases the reliance on external inputs and fossil fuels [36,47]. The introduction of perennial crops and pastures in crop rotations sequesters more carbon and stabilizes soil organic matter, reducing erosion and enhancing biodiversity, collectively contributing to lower energy consumption in agricultural operations [45].

Similarly, effective manure management increases soil fertility and reduces the need for synthetic fertilizers, which are energy-intensive for production and application. Effective manure management involves the use of composting to reduce CH_4 emissions from manure, the substitution of biofuel for fossil fuel consumption, and the adoption of targeted- and slow-release fertilizers to decrease the use of energy-intensive inorganic nitrogen fertilizers [10]. In addition, alternative and novel feeds, such as food industry byproducts, oilseed byproducts, and aquatic biomass, can be used to improve the efficiency (Table 1) and sustainability of meat production [18]. Thus, improved soil fertility leads to better crop and pasture yields, thereby reducing the energy required for additional feed production.

Increased feed efficiency reduces energy use. A higher feed efficiency means that less feed is required for the same amount of meat production, reducing the energy used in feed production, processing, and transportation [16]. Studies have shown that programmed and restricted feeding strategies can improve feed efficiency, leading to decreased feed intake and subsequently lowering enteric CH_4 emissions and nutrient loads in the environment [41]. Thus, efficient feed usage lowers the overall energy footprint of meat production and enhances economic and environmental sustainability.

Increased water use increases (Table 1) energy use [27]. Proper water management techniques such as keyline water management systems and MiG play a crucial role in reducing the need for energy-intensive irrigation [36]. Appropriate water management practices, such as rainwater harvesting and rotational grazing, reduce energy-intensive irrigation needs and maintain healthy soil moisture levels for vegetation growth [46]. Conservation tillage reduces the amount of tillage, which helps conserve soil and use available moisture more efficiently [48]. Agroforestry, which incorporates trees into agricultural systems, can improve nutrient availability and use efficiency, reduce erosion, and store carbon [50]. Thus, efficient water use conserves resources and reduces energy consumption associated with water extraction and irrigation systems.

Efficient water management techniques, such as drip and pivot irrigation, can minimize water wastage and reduce the energy required for pumping and distributing water, which is particularly crucial given that 40% of crop production relies on the 16% of agricultural land that is irrigated. Developing crops with high water-use efficiency and greater drought tolerance through biotechnology or conventional breeding can also significantly reduce the energy required for irrigation [50]. Additionally, the adoption of eco-agriculture systems, which emphasize the management of green water (naturally infiltrated into the soil) and blue water (water in rivers and aquifers), can enhance watershed functions and reduce the need for energy-intensive irrigation practices [17,52]. By focusing on sustainable practices, such as maintaining year-round soil vegetative cover and using vegetation barriers to slow water movement, agricultural systems can better manage water resources, reduce erosion, and enhance water infiltration, all of which contribute to lower energy use [52].

Management actions that increase the efficiency of water use or reuse water for multiple purposes can increase the effective water supply for human use without additional freshwater diversion from ecosystems [51]. Additionally, precision agriculture technologies allow the application of water only to the places where it is required, thereby optimizing the use of inputs and reducing energy consumption [65]. As water scarcity becomes more pronounced, with predictions indicating that by 2050, 59% of the world's population will face blue water shortages, and 36% will face both blue and green water shortages, efficient water management will be critical in mitigating the energy demands of agricultural systems [17].

Increased carbon sequestration decreases energy use. Practices that enhance carbon sequestration (e.g., maintaining healthy pastures and implementing agroforestry) might reduce the need for external inputs and the associated energy use. By promoting soil organic matter accumulation and increasing the aboveground biomass, these practices act as carbon sinks, offsetting GHG emissions [48]. For example, a unique soil-based carbon sequestration project integrating livestock, soil improvement, forestation, and CH_4 utilization has been found to remove GHG from the atmosphere [36]. Improved practices, including enhanced genetics, diets, and land management, have led to reductions in the carbon footprint of beef cattle despite many challenges, such as changes in soil carbon, that impact these estimates [13]. For example, a study on beef production systems in the Upper Midwestern United States found that pasture-finished beef had the highest impact for all categories, whereas feedlot-finished beef had the lowest impact [16]. Conservation agriculture has the potential to sequester soil carbon and contribute to climate change mitigation [46]. Thus, climate regulation through carbon sequestration mitigates the impact of climate change, stabilizes weather patterns, and reduces the need for energy-intensive adaptation measures.

Increased community awareness and engagement in sustainable practices such as agroforestry and rotational grazing reduces the reliance on fossil fuels and promotes energy-efficient practices, enhancing overall sustainability [18,36]. Policy coherence supports the adoption of CSA and the effectiveness of public policies, while tailored incentives modify the cost–benefit structure of agricultural inputs and outputs, reinforcing expected revenue streams and enabling the intensification of factor returns. This supports farmers in reallocating resources toward more resilient climate-smart practices [58]. Tailoring incentives to behavior increases the likelihood of CSA adoption, and by incorporating agroforestry and rotational grazing, communities can improve livestock productivity, reduce emissions, and enhance carbon sequestration, contributing to climate change mitigation [46].

Educating farmers about the benefits of sustainable agricultural intensification optimizes production and minimizes external costs, such as energy use, by improving pasture management and incorporating soil organic carbon (SOC) sequestration techniques [12]. Additionally, raising awareness about the importance of ES and the adverse effects of excessive nitrogen fertilization can lead farmers to adopt more efficient nutrient management practices, reducing the energy inputs associated with fertilizer production and application [50]. Community awareness campaigns are vital in educating both producers and consumers, fostering a more sustainable agricultural system that meets future food production needs while minimizing environmental impacts [53].

Because the conservation agriculture technique adopts minimum soil disturbance, permanent organic soil cover, and crop rotations, it can also be promoted through community education. These practices not only enhance soil health and fertility but also reduce the need for energy-intensive inputs like synthetic fertilizers and pesticides [63]. Moreover, community awareness can lead to the reform of pricing systems, particularly in energy, contributing to reduced energy consumption in agricultural systems [24].

3.7. Carbon Sequestration and Climate Regulation Loop

The carbon sequestration and climate regulation loop (B2) in Figure 1 is another balancing loop, as healthy pastures have robust vegetation that can sequester carbon from the atmosphere through photosynthesis. This process of soil carbon sequestration (Table 1) provides numerous benefits, including improved food security and offsetting fossil fuel emissions, which are linked to global challenges such as global warming, desertification, and biodiversity loss [19,66].

One of the primary ways in which healthy pastures contribute to improved soil structure is by promoting soil aggregation and enhancing the stability of soil organic matter. This, in turn, leads to better soil porosity and water infiltration. The action of plant roots and soil microorganisms plays a crucial role in this process, as they help bind soil particles together and create stable aggregates, resulting in improved soil structure and aeration [39,64].

Sustainable management practices, such as rotational grazing and reduced tillage, are particularly effective in enhancing soil organic matter levels in pastures. These practices are vital for maintaining soil fertility and structure. The presence of diverse plant species in pastures contributes to a robust root system that helps bind soil particles, reduces erosion, and improves water infiltration and retention [36,66]. While the integration of livestock in well-managed pastures can further enhance soil fertility by recycling nutrients through manure, it is important to avoid overgrazing and soil compaction, as these can lead to soil degradation and the loss of organic matter [11].

Enhancing grassland management involves several strategies, such as converting degraded cropland or woodland into grasslands, reducing grazing intensities, minimizing biomass burning, and improving degraded lands to reduce erosion and promote the growth of diverse grass species. These practices can significantly contribute to GHG mitigation [49]. Management-intensive rotational grazing, for example, has been shown to enhance forage production and quality in subhumid cool-season pastures, positively affecting biomass production [22]. Integrating pastures and animals in rotation with crops cultivated in no-tillage systems optimizes the beneficial characteristics of conservation agriculture, including carbon sequestration, increased biodiversity, improved nutrient cycling, and reduced economic risks [45].

No-till farming, which avoids disturbing the soil through plowing, is another effective practice for reducing carbon emissions by 30 to 35 kg C/ha per season and enhancing soil carbon storage by maintaining soil structure and organic matter [66]. Agroforestry practices, such as alley cropping and silvopasture, also contribute to carbon sequestration by producing trees and other crops on the same acreage, providing large quantities of carbon that are sequestered by the trees. These practices provide additional benefits, such as shade for grazing animals, reducing heat stress, and increasing growth performance and animal well-being [47]. Not only do these practices sequester carbon, but they also improve soil fertility and productivity, leading to higher crop yields and better livestock health, which are economically beneficial for farmers. For instance, using organic fertilizers and maintaining adequate pastures without overgrazing ensure a sustainable feed supply for cattle, supporting herd growth and market stability [30].

The carbon sequestered through these practices is stored in plant biomass and the soil, effectively reducing the amount of carbon dioxide in the atmosphere and contributing to climate regulation. To stabilize weather patterns and reduce the severity of climate change impacts, it is crucial to increase climate regulation efforts, which will benefit the overall ecosystem health. This, in turn, increases the need for more favorable conditions for sustainable pasture management, such as rotational grazing, the maintenance of proper stocking rates, AMP grazing, and the prevention of overgrazing. These practices help sustain pasture health, ensuring that pastures remain healthy and that they continue to sequester carbon [10]. It is important to note that increased meat production can reduce carbon sequestration if it leads to overgrazing, deforestation, or poor pasture management, which degrades the ability of land to sequester carbon. However, sustainable meat production practices, such as rotational grazing and improved pasture management, can enhance carbon sequestration by maintaining healthy vegetation and soil.

Healthy pastures not only improve soil structure and fertility but also enhance carbon sequestration [12]. The process of carbon sequestration contributes to climate regulation and affects vegetation growth and soil health. For example, prairie plants draw carbon deep into their root systems, enhancing soil health and biodiversity, which, in turn, leads to more effective carbon sequestration [36]. Practices such as MiG increase soil organic matter and microbial activity, leading to improved soil structure and fertility [39,45]. Additionally, biochar applications can increase the SOC content by 39%, while cover crops can enhance it by 15%, contributing to better soil health and crop productivity [64].

Sustainable pasture management reduces energy consumption, lowers GHG emissions, and enhances economic sustainability. For instance, management-intensive rotational grazing has been shown to enhance forage production and quality in subhumid cool-season pastures, contributing to both economic and environmental sustainability [22]. Improved soil fertility resulting from better manure management enhances vegetation growth, which, in turn, contributes to carbon sequestration. The carbon sequestered from healthy vegetation affects climate regulation, which can influence soil moisture and fertility. In terms of weather patterns and water availability, healthy vegetation and improved soil health can lead to more stable local climates and better water infiltration and retention, reducing the risk of droughts and floods (Table 1) [8,66].

3.8. Environmental Impact Loop

Beef production is a resource-intensive process that requires significant amounts of water and energy, which contributes to various environmental issues (Table 1), such as freshwater eutrophication, marine eutrophication, and terrestrial acidification [15,31]. The production process involves several sources of greenhouse gas emissions, including CH_4 from enteric fermentation and manure management, nitrous oxide from manure and slurry management, and carbon dioxide from land-use changes and fossil fuel usage [7]. These environmental impacts are closely linked to meat production and the environmental impact loop (R6), a critical reinforcing loop identified in Figure 1.

As meat production increases, this may lead to a higher environmental impact, which, in turn, negatively affects carbon sequestration [13]. Land-use changes associated with meat production, such as deforestation for pasture expansion, can significantly reduce carbon sequestration and increase carbon emissions [10]. Moreover, soil degradation caused by overgrazing and poor pasture management can diminish the soil's ability to sequester carbon and to regulate the climate [22].

To address soil degradation, significant investment in ecosystem management and restoration practices is required, as degraded agricultural landscapes are critical for achieving both agricultural productivity and biodiversity benefits [52]. Improved management practices (e.g., reducing grazing intensities, minimizing biomass burning, and enhancing degraded lands) can help mitigate greenhouse gas emissions by promoting better growth of grass species mixtures and reducing land erosion [49]. For example, Brazil's Low Carbon Agriculture program aims to restore millions of hectares of degraded pastures, highlighting the national and global importance of such initiatives for climate mitigation [12].

Within the agriculture sector, beef is a major contributor to GHG emissions, accounting for 41% of the total emissions in the livestock sector, which itself contributes 14.5% of the global anthropogenic GHG emissions [18]. Increased meat production can lead to higher GHG emissions, mainly CH_4, from enteric fermentation in ruminants and manure management [9]. To mitigate these impacts, efforts are expected to result in reduced resource consumption, waste generation, and greenhouse gas emissions. For instance, increasing the efficiency of animal production is an important route toward reducing environmental impacts as well as production costs [49]. The use of LCA to evaluate the environmental performance of meat production has identified key impacts, and reducing these impacts in beef production involves adopting sustainable practices that enhance animal health, environmental protection, and food quality [15].

When carbon sequestration decreases, an increase in climate regulation is expected, leading to more effective climate regulation and sustainable pasture management. These actions are expected to enhance healthy pastures, which will support further meat production. This creates a cycle in which each element amplifies the others, creating a reinforcing loop. Conversely, efforts to mitigate environmental impacts can reduce adverse effects associated with meat production.

Increasing production efficiency can lead to the same or higher output with fewer resources or livestock, thereby reducing the emissions intensity. This notion is supported by research in the Sardinian sheep sector, which found that eco-innovations that mitigate GHGs (improving animal management, animal feed production, feed crop cultivation management, and energy consumption) can lead to a reduction in emissions intensity [67]. Additionally, a study on the implementation of payment for environmental services in high-mountain farming found that its implementation led to a reduction in livestock farming and an increase in the maintenance of natural coverage of the territory, contributing to the reduction in emissions intensity [68].

4. Prospective Ecosystem Enhancements Within the Beef Cattle Production System

Beef cattle production systems harness essential ES, such as air, water, forage, and soil, which are crucial provisional services (Figure 2) for beef production. These systems also benefit from supporting services like the cross-pollination by bees for nutrient-dense forage, the soil nutrient cycling of manure, and conducive habitats, as well as cultural services that include community involvement and cultural support for farming [69]. By judiciously leveraging these ES, beef cattle production systems can enhance their efficiency and sustainability by applying ST-backed, agro-ecologically sound management (Loops 1 to 8; Figure 2) practices, ensuring a steady supply of beef while maintaining the health of the ecosystem.[1]

Natural resource and beef system managers play a pivotal role in this process by utilizing various strategies and tools to regulate the climate, augment water systems, and promote better soil health.[2] These efforts not only provide essential provisional services like meat, hide, and organic manure but also contribute to soil fertility and biodiversity (see note 2). Additionally, these systems could also support culturally enriched ecosystems that balance the soil–plant–animal interactions, which are vital for human well-being. The multifaceted impacts of well-managed cattle systems underscore their importance in achieving sustainable development goals (Figure 1). A beef supply chain that augments the ES in multiple dimensions is quintessential to the resilience and sustainability of the beef cattle production systems (see note 1). Each production cycle contributes to ES, enhancing soil fertility, supporting biodiverse environments, and providing cultural benefits. In summary, beef cattle production benefits significantly from ES and, in turn, contributes to these services, creating a sustainable and resilient system that supports both ecological and human well-being (Figure 2).

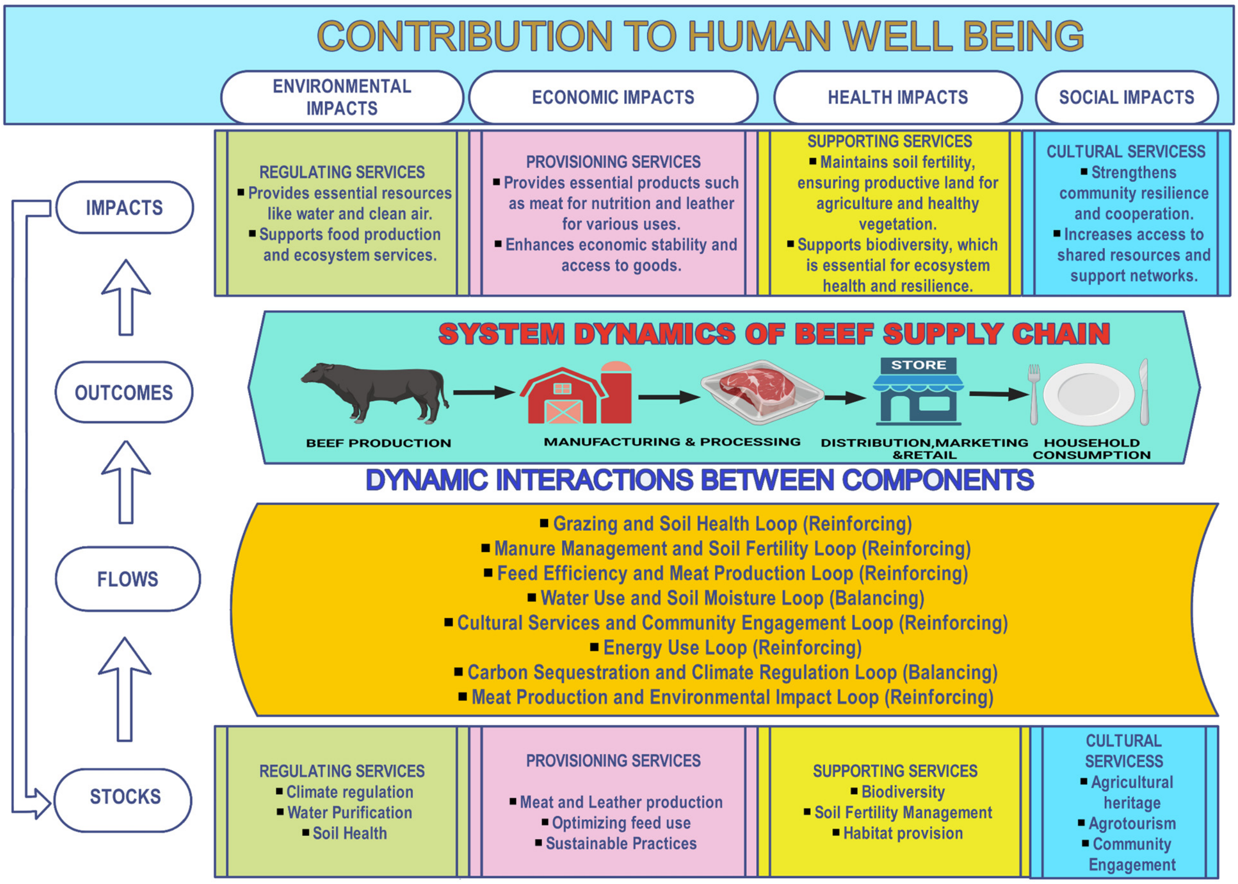


Figure 2. The economics of ecosystems and the biodiversity evaluation framework for agrifood systems applied to beef production systems. Beef production relies on stocks such as clean air, pure

water, healthy soils, and biodiverse ecosystems. Using the optimally managed eight feedback loops, beef supply chains will upregulate ecosystem services (pure water, clean air) and provide nutritious meat, leather, and economic growth while also supporting soil health, biodiversity, and ecosystem resilience, eventually impacting community well-being. Adapted from Zhang et al. [70].

4.1. Regulating Services

Reducing GHG emissions and enhancing soil health are crucial for regulating beef cattle production services. Practices such as improved manure management, feed additives, and CH_4 capture technologies can mitigate emissions [71]. Enhancing soil health through cover cropping, reduced tillage, and organic amendments can increase carbon sequestration and improve water retention (SDG 6: Clean Water and Sanitation), thereby contributing to climate regulation and water quality [64,72]. AMP grazing can mitigate climate change through SOC sequestration, offsetting GHG emissions, improving forage productivity and recovery, and enhancing soil health and water quality by reducing soil erosion and improving water infiltration [10]. Ijaz et al. [71] specifically discussed practical ways to lower GHG emissions in livestock yards, such as phase feeding, biofiltration, reducing the manure storage time, and anaerobic digestion technology, which can help reduce emissions and enhance regulating services (Figure 2). Regulating services can also be associated with fire prevention and lowering of the fuel load in grassland, brush covers, or woodland. Ruminant grazing has been increasingly recognized for its role in fire prevention by reducing refined fuels, such as grasses and brush, which can mitigate the severity and spread of wildfires. This practice, supported by long-term studies in rangelands, shows that planned herbivory (SDG 15: Life on Land) can effectively manage wildland fuels, thereby enhancing fire resilience and contributing to ecosystem management [73,74].

4.2. Provisioning Services

Strategies that improve feed efficiency and integrate sustainable practices are essential for enhancing provisioning services (Figure 2). By optimizing feed conversion ratios and reducing waste, beef cattle production (SDG 2: Zero Hunger) can be increased while minimizing environmental impacts (SDG 12: Responsible Consumption and Production). Sustainable practices such as rotational grazing and agroforestry can maintain long-term productivity and resilience. Rotational grazing improves grazing land, ensures surface cover, reduces erosion, increases fodder productivity, enhances forage quality and digestibility, boosts system productivity, and reduces CH_4 emissions per unit of livestock weight [46]. Others [13,16] found that the carbon footprint of beef production varies depending on the production system, with feedlot-finished beef having a lower carbon footprint compared with pasture-finished beef, while grass-finished beef falls in between the two categories. Some authors [41,71] have emphasized the effectiveness of phase feeding and manure management practices such as biofiltration, reduced storage time, and anaerobic digestion in reducing emissions. This can lead to an increased efficiency of gain (SDG 1: No Poverty) relative to ad libitum feeding, thereby decreasing the environmental footprint of the cattle-feeding industry. Feeding cattle corn-based diets can lead to higher CO_2 emissions from manure but lower CH_4 and nitrous dioxide (N_2O) emissions under certain soil conditions, ultimately impacting greenhouse gas emissions when the manure is applied to different soil types (SDG 13: Climate Action). This variation highlights the interaction between diet, manure management, and soil type in determining the environmental footprint of livestock production [75,76]. Agroforestry, another sustainable practice, can improve animal performance through better pasture quality and a favorable microclimate from tree shading and protection from harsh weather while also increasing carbon sequestration by restoring degraded rangelands and altering land uses, thus reducing the overall GHG produced by livestock [18]. The reinforcing loop 6 in Figure 1 is directly dependent on the cattle inventory, and an increase in the cattle population without technical improvement will lead to exponential growth of the impact. Conversely, efforts to improve production levels with good practices on nutrition, reproduction, and health would lead to balancing loops, in which an increase in production per head will cause a possible reduction in the number of animals (SDG 9: Industry, Innovation, and Infrastructure) and maintenance feed costs and, consequently, a reduction in emission intensities, or footprints, as kg of emissions per unit of product [67]. It would cause the mitigation of environmental impacts, which can reduce the adverse effects associated with meat production.

4.3. Supporting Services

Supporting services, including biodiversity conservation and soil fertility management, are vital for sustainable beef cattle production. The maintenance of diverse plant species in grazing lands supports pollination (SDG 15: Life on Land) and pest control, as has been demonstrated by several authors [77–81]. Conservation of wild species and the management of soil, water, fire, and vegetation can transform crop fields into valuable habitats for species, enhance habitat quality, and improve soil health [52]. Wild fauna associated with beef is also primarily represented by wild, often rare, bird species associated with grazing activities or insectivorous birds that maintain diverse plant species in grazing lands by supporting pollination, pest control, and soil health. Best practices include planting high-productivity, drought-tolerant (SDG 13: Climate Action), and deeper-rooted fodder grasses and legumes; improving the vegetation community by planting high-productivity grasses and legumes; and implementing controlled grazing through stocking rate management and rotational grazing to improve the grazing land and ensure surface cover [10,46]. Sustainable grazing practices prevent overgrazing and soil erosion while enhancing soil fertility through composting and nutrient cycling, as discussed by de Faccio Carvalho et al. [45], and they ensure productive pastures and healthy ecosystems.

4.4. Cultural Services

Enhancing cultural services in beef cattle production through ST is a holistic approach that integrates various dimensions to improve sustainability and resilience in farming. ST is crucial for understanding the multifaceted impacts of beef cattle production and recognizing the interconnections (SDG 17: Partnerships for Goals) within the agricultural ecosystem [1,49]. One significant aspect is the role of agricultural heritage systems (SDG 11: Sustainable Cities and Communities) in supporting biodiversity, promoting sustainable land use, and maintaining cultural landscapes. Integrating agrotourism into beef cattle production provides economic benefits and helps preserve and promote local culture and traditions, underscoring the importance of a systems approach to recognizing and leveraging cultural assets in agricultural practices [82]. Zhang [43] and Daniel and Robin [59] highlight the influence of Globally Important Agricultural Heritage Systems, which foster community engagement (SDG 3: Good Health and Well-being) and cultural preservation, which are crucial in supporting rural economies and communities. In regions such as Indonesia, enhancing community-based practices and local knowledge through ST involves identifying and strengthening the linkages between cultural heritage and modern agricultural techniques [60]. Agrotourism, which involves opening farms to visitors, can provide economic opportunities for rural communities while promoting cultural exchange and education about traditional farming practices. Additionally, community-based practices such as participatory decision making (SDG 17: Partnerships for Goals) and collective action can foster social capital and resilience within rural farming communities, contributing to the preservation of cultural heritage [48]. Sims and Heney [63] emphasize the importance of conservation agriculture in promoting sustainable practices that align with cultural and community values. Furthermore, Tona [49] and Turner et al. [2] highlight the need to balance the intensification of beef cattle production with the preservation of cultural services, ensuring that advancements do not undermine traditional practices and community well-being. Hence, enhancing cultural services in beef cattle production through ST requires a comprehensive understanding of the interplay between cultural heritage, community practices, and modern agricultural techniques. By valuing and incorporating traditional knowledge and cultural practices, resilient and sustainable agricultural systems can be created that benefit both the environment and local communities, supporting biodiversity, sustainable land use, cultural identity, and economic viability (SDG 8: Decent Work and Economic Growth) in rural areas [43].

5. Challenges and Opportunities

The implementation of ST in beef cattle production faces challenges, such as resistance to change, lack of awareness, and limited resources. However, opportunities exist to leverage technological advancements (SDG 4: Quality Education), such as those discussed by Pampori and Sheikh [83], and policy support, including incentives for sustainable practices, as noted by van Asseldonk et al. [58]. Policy approaches for ES applying participatory methods and systemic modeling at the territorial level have been published for sheep production [67] and beef cattle [68]. These studies show how public pressure on environmental issues requires large public investments that can be directly oriented to increase livestock efficiency to reduce footprint intensities while indirectly enhancing capacity building (SDG 9: Industry, Innovation, and Infrastructure) and ES's role, changing from dangerous reinforcing loops (exponential impacts) to sustainable balancing loops (goal seeking for system capacity) [67]. Otherwise, ST and SD can model the ES payment in woodland in association with beef production. However, policies based on payments are only effective during the payment periods if they are not adequately supported by systemic loops that permanently make system changes [68]. Collaborative efforts among stakeholders, perhaps supported by participative modeling, and living labs with systemic group model building (SDG 17: Partnerships for the Goals), can help overcome the barriers to adoption and side effects from unintended consequences [67]. Adopting the approach shown by Atzori et al. [67] to the causal diagram in Figure 1 for ES provided by the beef cattle sector might also have a broad impact on communities and rural areas, which fits in with pursuing the sustainability goals of the UN agenda by 2030.

6. Conclusions

Future research and development can further refine ST applications for systemic understanding, enhancing ES, and promoting sustainable practices in beef cattle production that would align with the United Nations' Sustainable Development Goals. ST offers a robust framework for enhancing sustainable intensification practices and connecting with ES in beef cattle production. Policymakers and managers can develop more effective and sustainable management strategies by recognizing the interconnectedness of ecological and agricultural systems; in particular, food provisioning goals and their associated ES or sustainable goals. This approach addresses current challenges and ensures long-term health and resilience for human and ecological systems. Embracing ST is crucial for improving policy formulation, addressing natural resource decision-making, and fostering the sustainable development of beef cattle production.

Author Contributions: Conceptualization, L.O.T., D.C.J., A.S.A., K.K. and H.M.M.III; methodology, L.O.T., D.C.J., A.S.A., K.K. and H.M.M.III; resources, L.O.T., D.C.J., A.S.A., K.K. and H.M.M.III; data curation, L.O.T., D.C.J., A.S.A., K.K. and H.M.M.III; writing—original draft preparation, L.O.T., D.C.J., A.S.A., K.K. and H.M.M.III; writing—review and editing, L.O.T.; visualization, L.O.T. and D.C.J.; supervision, L.O.T.; project administration, L.O.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

Notes

[1] https://ec.europa.eu/eip/agriculture/en/focus-groups/sustainable-beef-production-systems.html (accessed on 20 October 2024).
[2] https://grsbeef.org/core-principles/natural-resources/ (accessed on 20 October 2024).

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