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Incorporating biodiversity into the sustainability assessment of livestock systems using comprehensive life cycle assessment: A mini-review

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Livestock significantly contribute to biodiversity loss, primarily due to changes in land use, overexploitation of natural resources, pollution, and climate change. Intensive farming systems that depend heavily on resource inputs accelerate the decline of species and exert immense pressure on biodiversity, ultimately making the industry unsustainable. Identifying hotspots and quantifying their impacts along the value chain of animal products help producers and policymakers make informed decisions and provide insights to guide consumers toward more environmentally conscious purchasing. Life cycle assessment (LCA) provides a holistic approach to assessing the environmental footprint (EF) throughout the life cycle of a product or service. However, ecosystem services, such as biodiversity, are often not integrated into LCA, particularly in the context of livestock systems. Existing studies and methodologies frequently fail to illustrate the impacts of biodiversity under various management practices. In addition, the majority of these studies focus on a single midpoint impact category related to land use change, which is based on the species–area relationship (SAR) and metrics at the species level. However, due to the dynamic and complex nature of biodiversity, relying on a single midpoint impact or metric alone is insufficient to capture the full spectrum, and it does not provide a comprehensive understanding of the impacts. In addition, the lack of consensus on characterization factors (CFs), limitations in data availability (i.e., conservation status of taxa at local and regional levels), and challenges in assigning weights to taxa and ecological functions based on their significance are key limitations that need to be addressed in future LCA studies.

KEYWORDS

biodiversity, livestock farming, biological footprint, life cycle assessment, ecosystem services

1 Introduction

An unprecedented level of biodiversity loss has been observed in recent decades, with a decline of 69% in biodiversity between 1970 and 2018 (WWF, 2022). Habitat loss caused by the conversion of natural ecosystems for food and agricultural production, as well as habitat homogenization and degradation arising from agricultural intensification, has been identified as the primary reason for this trend (IPBES, 2019). Approximately 45% of the habitable Earth's surface has been transformed into agricultural land (Ritchie and Roser, 2019), with more than two-thirds of this area utilized for pasture and livestock feed production (Benton et al., 2021). Increased reliance on large amounts of fertilizers and machinery, overgrazing, and higher stocking densities in modern intensive livestock

production systems also accelerate the loss of biodiversity (Benton et al., 2021). Furthermore, the livestock sector indirectly contributes to the decline of species and biodiversity by altering the global climate through the emission of nearly 12% of anthropogenic greenhouse gases (GHG) from global animal protein production (FAO, 2022; IPBES, 2019), polluting and contaminating water and land (i.e., eutrophication and acidification) (FAO, 2006; FAO, 2018), and contributing to the spread of diseases and invasive species (FAO, 2006; FAO, 2018). On the contrary, livestock systems are also known to perform an often-overlooked role in promoting diversity and shaping ecosystem functioning. For instance, studies have shown that well-managed rangelands with moderate grazing levels foster greater diversity compared to under-grazed or overgrazed systems, highlighting the significance of the interplay between biodiversity and livestock (Geß, 2020; Mathewos et al., 2023). However, the increasing pressure to meet the growing demand for animal-sourced products of the expanding human population continue to strain local biodiversity and its ecological functioning, jeopardizing the sustainability of these production systems (FAO, 2018).

It is essential to identifying and quantifying biodiversity under various production and management scenarios along the product value chain using life cycle assessment (LCA) to gain a comprehensive understanding of sustainability and to make informed decisions. However, the current LCA methodology often overlooks the multifunctionality (e.g., draft power, financial asset and savings, social status, and biodiversity) of smallholder extensive or semi-intensive livestock farming systems, resulting in a greater footprint per unit of product compared to intensive systems (Gerber et al., 2013). Despite the presence of numerous LCA impact assessment methods, such as LC-IMPACT (Verones et al., 2020) and Impact World+ (Bulle et al., 2019), incorporating biodiversity, recent literature points out several limitations associated with these models and their applications. For instance, Teillard et al. (2016) emphasized the importance of improved assessments in the context of agricultural production with the inclusion of concepts from landscape ecology, such as landscape heterogeneity and habitat fragmentation, and the use of agro-ecological models to account for agricultural intensity in biodiversity loss. Similarly, Souza et al. (2015) highlighted the need for consensus on life cycle impact indicators, particularly in land use modeling. However, the literature on incorporating biodiversity into LCA models is still evolving, and only a few regional studies have utilized and applied these concepts to livestock production systems (Mueller et al., 2013; McClelland et al., 2023). Our goal was to perform an extensive literature review in order to identify viable biodiversity indicators and indices that are appropriate for livestock production, particularly for dairy and beef systems. We also aimed to provide an overview of current LCA impact assessment methods that incorporate biodiversity within the context of livestock, such as ReCiPe 2016 (Huijbregts et al., 2016). We also discussed the challenges and shortcomings associated with these methods and suggested potential future directions. Building on recent reviews (Teillard et al., 2016; Damiani et al., 2023) and placing particular emphasis on livestock species, this mini-review serves as a summary guide to different approaches for tailoring existing LCA methodologies, particularly by using multiple ecosystem indicators as midpoint impacts and regional characterization factors (CFs), which indicate the biodiversity damage per unit area. This framework will allow for a comparison of the ecological footprints associated with different livestock farming practices.

1.1 Database search and selection of new article

A preliminary literature survey was conducted using the scientific databases such as Google Scholar and Web of Science, with keywords such as “Biodiversity metrics,” “Biological footprint,” “Ecological footprint,” “Life cycle assessment,” “Livestock farming,” “Ruminant systems,” and “Sustainable farming”. A total of 328 peer-reviewed articles published in English were filtered, and only 38 studies related to LCA incorporating biodiversity and biodiversity metrics in the context of livestock farming, particularly ruminant systems, were selected after excluding duplicates and irrelevant studies (i.e., non-LCA) by scanning the titles and the abstracts. In addition, five peer-reviewed journal articles published in English were identified through snowballing the above-mentioned articles, and nine more articles were included based on consultation with experts. In total, 52 articles were selected for this mini-review.

2 Importance of biodiversity in livestock production

Biodiversity provides several direct and indirect services that contribute to ecosystem functions. According to the Millennium Ecosystem Assessment (MEA) (2005), these services are classified into four categories, namely, provisioning, regulating, cultural, and supporting services, all of which are essential for human existence. Biodiversity plays a key role in shaping the food system, including livestock production, by providing biomass that accounts for 18 and 37% of the global human calorie and protein supply, respectively (Benton et al., 2021). Regulating services, such as water regulation, pollination, and pest control, and supporting services, such as soil formation and nutrient recycling, fulfill the natural resource requirements for continuous livestock and livestock feed production (Teillard et al., 2016). For example, 35% of global crops including important livestock feed crops, such as Alfalfa (*Medicago sativa*), are pollinated by animals (Klein et al., 2006), whereas pest and weed controlling agents such as soil microbes and soil nematodes are essential to maintain and manage rangelands and pastures for livestock grazing (Bale et al., 2007). Similarly, other ecosystem services, such as climate change regulation through carbon sequestration, water purification, and air quality regulation, buffer the impacts, such as climate change and pollution (M.E.A., 2005), arising from livestock production. However, dependence on biodiversity and its ecological services varies across different production systems. For example, extensive production systems, such as crop-livestock integrated systems and organic production systems, directly rely on biodiversity and its ecological services, such as nutrient recycling, pollination, and natural pest control (Pfiffner and Stoeckli, 2023). However, intensive livestock farming practices greatly depend on human inputs and have a low reliance on biodiversity, except for a few indirect services such as feedstock and biomass production.

3 Incorporating biodiversity in life cycle assessment studies

As with other environmental footprints (EFs), such as carbon and water footprints, a biodiversity footprint (BF) accounts for

trade-offs related to biodiversity along the supply and consumption chain of a product or a service. This provides a wealth of information on the impacts on biodiversity resulting from resource utilization and emissions associated with obtaining the end product. Thereby, a BF helps reveal the contribution of a particular organization or sector to biodiversity decline. However, an ecological footprint that quantifies the ecological impact in terms of biologically productive land required to compensate for anthropogenic resource usage and GHG emissions does not necessarily reflect or suggest a correlation with the biodiversity footprint (Hanafiah et al., 2012).

LCA serves as a holistic tool for assessing the EF of livestock products, although most LCA studies do not include ecosystem services or biodiversity in their assessments (Teillard et al., 2016; Myllyviita et al., 2019; Crenna et al., 2020). For instance, the most recent livestock LCA conducted in the USA focused on carbon footprint (Thoma et al., 2013; Naranjo et al., 2020; Uddin et al., 2021; Aguirre-villegas et al., 2022). Therefore, excluding biodiversity from LCA often makes the sustainability assessment biased. However, recent developments in biodiversity LCA methods have identified ways to incorporate biodiversity into LCA models to assist in uncovering impacts on biodiversity from both on-farm and off-farm activities (e.g., feed production, energy generation) (Curran et al., 2016; Lindner et al., 2021; Marques et al., 2021; Damiani et al., 2023). In addition, such assessments will permit comparisons of different products and services (Winter et al., 2017), deriving from various management practices and regions.

LCA methodology for assessing biodiversity oversees the impact pathways leading to biodiversity loss at both regional and global levels (FAO, 2020). Each inventory item (i.e., the land area transformed or occupied) is translated into its damage impacts by CFs through a life cycle impact assessment model to provide comparable impact units (Souza et al., 2015) expressed in relation to a functional unit and within a defined system boundary. For example, studies in the context of livestock production often express biodiversity impacts per liter of milk, kilogram of carcass, or kilogram of protein, where system boundaries are set at a farm-gate level (FAO, 2020) to account for all stages of production. Due to the significant impact of livestock farming on habitat conversion, the majority of these life cycle impact assessment models rely on land use for evaluating the impacts of biodiversity loss (Souza et al., 2015; Teillard et al., 2016). These models are based on the species–area relationship (SAR) ecological model (Souza et al., 2015; Teillard et al., 2016), which assumes a positive correlation between the number of species and land area and uses species richness as a proxy for biodiversity (Lindner et al., 2021). Several methodologies, such as ReCiPe (Huijbregts et al., 2016), have been designed by incorporating multiple midpoint impact categories—parameters that are between inventory data and the endpoint of the cause-effect chain for a particular impact category (Bare et al., 2000)—such as climate change, eutrophication, water use, ecotoxicity, invasive species, and land use. These methodologies aim to provide a comprehensive understanding of the endpoint impacts—environmental damage aggregated and summarized from midpoint impacts (Hardaker et al., 2022) of biodiversity loss—particularly in the context of livestock systems (Table 1; Teillard et al., 2016; Crenna et al., 2020).

4 Biodiversity metrics as indicators

Understanding and assessing changes in biodiversity are fundamental to conservation and investigating the sustainability of any ecosystem. Biotic indicators, defined as species or groups of species that reflect the state of an environment (Gerhardt, 2002), provide insights and offer quantifiable and interpretable means of assessing the impacts arising from disturbances or changes in the land use pattern, and they also provide an effective way to evaluate and follow up on conservation efforts (Duelli and Obrist, 1998; Büchs, 2003; Clergué et al., 2005; McClelland et al., 2023). However, due to the dynamic nature and complexity of biodiversity, as well as cost and time constraints, interpretations rely on a limited set of key indicators, selected based on scientific reliability, repeatability, and the underlying conservation goals (Büchs, 2003; Clergué et al., 2005). For example, McClelland et al. (2023) developed a biodiversity integrity index using indicators from eight thematic categories: habitat protection, habitat change, wildlife conservation, invasive species, aquatic biodiversity, off-farm feed, landscape heterogeneity, and ecosystem services to assess the performance of the ecosystem. To gain a comprehensive understanding of biodiversity, one should incorporate indicators to represent the principal components of biodiversity (genetic, species, and habitat) at every three dimensions (composition, structure, and function) (Curran et al., 2016; Teillard et al., 2016; McClelland et al., 2023), as well as indicators to reflect management practices (i.e., livestock density), particularly for human-dominated landscapes (Herzog et al., 2013).

Species richness (the number of species within a defined region) and species evenness (which accounts for the number of species and their relative abundance within a community) are widely used direct measures of biodiversity (Moore, 2013). Since sampling the entire biotic community is practically infeasible, taxa that are ecologically important and sensitive to environmental factors are often selected as suitable representatives of biodiversity correlates (Büchs, 2003). For example, in a livestock system, representatives of major ecological functions, such as primary production (e.g., vascular plants), decomposition and nutrient recycling (e.g., soil microbes, nematodes, and earthworms), and pest control (e.g., spiders), could provide a better understanding of ecosystem functioning (Herzog et al., 2013). In addition, indicator species—those that respond to changes in the environment (Clergué et al., 2005)—such as aquatic and terrestrial invertebrates, algae, and plankton, provide insights into the health of the ecosystem, which is threatened by excessive discharge of nutrients, chemicals, and manure from livestock farming. Furthermore, arthropods in general receive widespread recognition as key taxa for reflecting overall species diversity, as they account for approximately 65% of all multicellular species (Duelli and Obrist, 1998; Herzog et al., 2013).

Primarily based on species composition, a number of biodiversity metrics have been designed with the intention of assessing the state of and the influence on biodiversity. For example, metrics such as the mean species abundance (MSA) and the living planet index serve as state indicators of local ecosystem intactness and global decline in species, respectively (Teillard et al., 2016; Rossberg, 2022). In contrast, potential disappearance fraction (PDF), which compares original species richness to the fraction remaining after human intervention, is widely used as a footprint metric, particularly in the context of LCA studies with multiple midpoint impact categories

TABLE 1 Life cycle assessment (LCA) methodologies that incorporate biodiversity in the context of livestock.

Citation	LCA methodology	Midpoints (impact category)	Biodiversity metrics	Biodiversity proxy
Huijbregts et al. (2016)	ReCiPe 2016	Land use Climate change Acidification Eutrophication Ecotoxicity	PDF	Species composition
Verones et al. (2020)	LC Impact	Land use Climate change Acidification Eutrophication Ecotoxicity	PDF	Species composition
Bulle et al. (2019)	Impact World+	Land use Climate change Acidification Eutrophication Ecotoxicity	PDF	Species composition
Weidema et al. (2008)	StepWise	Land use Climate change Acidification Eutrophication Ecotoxicity	Biodiversity adjusted Hectare Year (BAHY)	Species composition
Frischknecht et al. (2006)	EcoScarcity	Land use	Eco-points (UBP)	Species composition
Jeanneret et al. (2014)		Land use		Species composition
Rosenbaum et al. (2008)	USEtox	Ecotoxicity		
Verones et al. (2022)	GEP		Global species extinction	Species composition
Chaudhary and Brooks (2018)	LUIS	Land use	PDF	Species composition

(Goedkoop et al., 2008; Table 1). Although the MSA was initially developed in the context of the GLOBIO3 modeling framework as a state indicator, it has also been used in LCA to translate several midpoint impact categories into biodiversity impacts at the end point, especially within the livestock sector (Alkemade et al., 2009; Teillard et al., 2016). Despite high spatial variation (regional and global) of these metrics in pressure-state-response (PSR) and LCA frameworks, numerous metrics are being tailored and developed to suit different methodologies and management practices, such as confined and grazing systems of ruminants.

5 Research gaps, limitations, and future developments

One of the major limitations of current LCA models is that most account only for a single midpoint impact category, particularly land use change, in assessing biodiversity impacts (Souza et al., 2015; Teillard et al., 2016) in livestock systems. Although the livestock sector is a primary contributor to habitat change, other impacts associated with livestock production, such as climate change, eutrophication, overexploitation of resources, and spread of invasive species, are overlooked in LCA studies (Teillard et al., 2016). Moreover, land use ecological models that depend on the SAR are criticized for being oversimplified (Souza et al., 2015)

and fail to account for positive contributions to biodiversity (Teillard et al., 2016). For instance, in well-managed semi-natural grasslands, extrapolation of reduction in land area to species loss can result in incorrect interpretations (Souza et al., 2015). In addition, the use of potential natural vegetation as a land cover reference to estimate the impacts on biodiversity fails to distinguish between relative intrinsic values (e.g., diversity, ecosystem services) and productivity, assigning the same weight to land use change impacts across different habitat types (Curran et al., 2016; Teillard et al., 2016). Another disadvantage is that these models rely on a single metric (e.g., MSA, PDF), primarily at the species level (Table 1; Winter et al., 2017; Crenna et al., 2020; Lindner et al., 2021), and rarely account for functional attributes (e.g., species functional traits and ecosystem services) (Teillard et al., 2016). Therefore, they are unable to capture the full scope of biodiversity (Lindner et al., 2021; Marques et al., 2021), including species extinction (Teillard et al., 2016). Furthermore, these indicators do not account for ecological or conservational values, such as endemism and rarity, to demonstrate the individual contribution to biodiversity (Chaudhary and Brooks, 2018) and to illustrate taxonomic significance. Few LCA models and indices have been developed to suggest higher biodiversity and conservation value for rare and unique species compared to common species. However, the development of these models is constrained due to limitations in ecological data at the regional and global scales, challenges in

assigning weighting factors for indicators based on their relative ecological importance (Herzog et al., 2013), and the lack of consensus on CFs (Chaudhary and Brooks, 2018). For example, the IUCN Red List, which serves as a database for ecological studies, is less reliable at the global scale, and only a few species have been evaluated and listed at the regional level (Duelli and Obrist, 2003). Frischknecht and Jolliet (2016) recommended the determination of CFs at different levels (e.g., global, regional) and for different ecosystem types, while other studies have suggested the use of multiple indicators and drivers to investigate impacts on biodiversity across different dimensions and to include spatial details in impact assessments (Crenna et al., 2020), aiming to address the existing weaknesses in current LCA studies. Alternatively, other approaches and tools, such as the PSR model, are widely used in assessing the impact on biodiversity at the local scale, where causal indicators translate the pressure and state of the environment (FAO, 2020). Although the PSR framework facilitates interpretation and decision-making, it fails to provide information on impacts across the life cycle of a product, especially off-farm impacts on biodiversity such as livestock feed production (Teillard et al., 2016), and is therefore unable to provide insights into BF. However, the recent Biodiversity Multi-Scale Assessment of Product Systems (BioMAPS) framework proposed by Maier (2023) integrates ecological, conservation, and LCA requirements, including land use types and management practices, to assess impacts and risks at regional and global levels by scaling up from the local scale.

6 Conclusion

Biodiversity assessment is an important part of evaluating the sustainability of livestock production, as livestock farming has a significant impact on biodiversity depletion. Studies incorporating biodiversity in the LCA framework allow the identification of hotspots and quantification of biological impacts across the life cycle of animal products from various origins. Despite the availability of several models and methodologies, capturing the full scope of biodiversity in these studies is challenging due to its complexity and the limitations and weaknesses associated with these models. Regardless, these approaches offer valuable insights for potential interventions and mitigation strategies. Incorporating multiple indicators for different ecosystem functioning and management practices to reflect multiple

dimensions of biodiversity would improve the reliability of LCA studies when comparing various livestock products.

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