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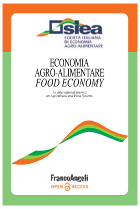

Grazing Impacts on Biodiversity, Carbon Cycle, Water Efficiency, and Animal Welfare: Review

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Abstract

This review examines the role of pasture-based livestock systems in promoting agri-environmental sustainability across four key dimensions: biodiversity, water-use efficiency, carbon cycle, and animal welfare. Despite growing political and scientific interest in extensive grazing, the existing literature remains fragmented and limits a comprehensive understanding of grazing's multidimensional impacts. To address this gap, we conducted a review of studies published between 2010 and 2025, following the Cochrane Handbook and applying the PICO (Population, Intervention, Comparison, Outcome) framework. The analysis focused exclusively on studies conducted in Europe to explore the state of the art on the topic and analyze future policy implications. The results indicate that moderate and well-managed grazing improves biodiversity, increases water-use efficiency, and promotes soil carbon sequestration, especially through rotation practices and tree integration. Access to pasture improves animal welfare, although outcomes vary depending on infrastructure and environmental conditions. The review emphasizes the need for integrated approaches that combine traditional knowledge, environmental design, and precision tools to maximize the sustainability of grazing systems.

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Introduction

Agriculture plays a crucial role in safeguarding ecosystem services, food security, and landscape preservation. However, demographic expansion, resource competition, geopolitical tensions, and climate change are placing increasing pressure on agricultural systems. In this context, halting biodiversity loss is a priority for the European Union, as outlined in the Farm to Fork and Biodiversity 2030 Strategies (Fraser *et al.*, 2022). The transdisciplinary One Health approach can strengthen resilience and prevention against environmental risks, antimicrobial resistance (AMR), and climate change (Rodriguez, 2024). Within agri-livestock systems, the debate around production intensification is growing. Extensive farming systems, through the diversification of grazing surfaces and species, promote biodiversity and soil fertility (Delaby *et al.*, 2020).

Despite growing interest in these systems, literature lacks comprehensive data on the environmental impact of livestock farming, as most studies have primarily focused on carbon footprint (Tittonell, 2021; Opio *et al.*, 2013), neglecting other aspects such as biodiversity, land stewardship, energy efficiency, and sociocultural values.

Elorriaga *et al.* (2013) highlight that the concentration of manure in intensive farming systems and the frequent use of antimicrobials result in significant environmental impacts, including water resource pollution with potential negative consequences for human health. Similarly, Jechalke *et al.* (2014) emphasize that manure spreading practices associated with such production systems may pose high contamination risks and promote the development of antimicrobial resistance.

In the present review, we adopt the PICO framework (Population, Intervention, Comparison, Outcome) to define the scope of analysis and guide the construction of search strings. Following Cochrane guidelines (Cumpston *et al.*, 2024), the study is based on the effects of pasture-based grazing systems in relation to four critical dimensions of agro-environmental sustainability: biodiversity, water use efficiency, carbon cycle, and animal welfare.

1. Background

In recent years, consumers have shown growing interest in purchasing products derived from sustainable agricultural systems, which are perceived as more respectful of environmental integrity and animal welfare. This trend reflects a broader societal concern over the ecological footprint of food production and a demand for transparency in how ecosystems are managed and preserved. Ecosystems provide essential services, such as food provision, water regulation, and climate mitigation, that underpin human wellbeing and economic development. Yet, these contributions are rarely reflected in traditional economic indicators, creating a disconnect between environmental value and policy action (Vargas *et al*., 2024). Across many regions, especially those undergoing accelerated agricultural intensification, the lack of long-term planning and water resource monitoring has led to significant sustainability challenges, particularly in terms of water use (Barsotti *et al*., 2022). At the same time, the abandonment of traditional land use practices, common throughout Europe in recent decades, has had profound impacts on agricultural landscapes, resulting biodiversity loss (Ponzetta *et al*., 2010). Indeed, it is estimated that 75% of grassland habitats in the European Union are in poor or bad condition, with land abandonment and overgrowth representing key threats (Hessle *et al.,* 2023). The integration of food production with biodiversity conservation has thus emerged as a critical challenge for sustainable development (Gallé *et al*., 2020). This is particularly urgent in the context of the ongoing need for ecological intensification of farming systems, improving agricultural productivity while minimizing environmental degradation and maintaining ecosystem functions (Beye *et al.,* 2019). Future grazing systems are expected to play a central role in this transition by supplying nutrient- dense food within lower-input systems that reduce reliance on fossil fuels and agrochemicals, and enhance environmental, biodiversity, and animal welfare outcomes (Delaby *et al*., 2020). Lower-input pasture-based systems offer several advantages: they utilize feed sources inedible to humans (e.g., grasslands) rather than human-edible grains (e.g., soya), and they reduce feeding costs and the environmental footprint of production. Additionally, these systems often align with consumer preferences for higher animal welfare and environmentally sustainable meat products. In this context, the preservation and promotion of autochthonous livestock breeds are of strategic importance. These breeds not only embody genetic diversity crucial for adaptation to local environments, but also support rural development, cultural identity, and food and nutrition security, especially in marginal and pasture-based systems (Agradi *et al*., 2023). According to Devincenzi *et al.* (2021), grazing behaviour management plays a crucial role in improving animal welfare, product quality, and ecosystem services.

2. Materials and methods

This review was conducted following the methodological principles outlined in the Cochrane Handbook for Systematic Reviews of Interventions, and the review design was structured using the PICO model (Population, Intervention, Comparison, Outcome) (Table 1) (Sala *et al*., n.d.) to formulate the research question and organize the thematic domains. The aim was to identify and synthesize scientific literature on the environmental and animal welfare effects of pasture-based grazing systems.

Table 1 - PICO model

P	Population/Problem	Livestock production systems
I	Intervention	Effects of grazing on biodiversity, water use efficiency, carbon sequestration, and animal welfare
C	Comparison	Comparison between livestock systems and farming methods at the European and global level
O	Outcome	Scientific evidence on the most frequently addressed and associated sustainability themes

Source: Authors' elaboration.

To ensure methodological rigor and transparency, inclusion and exclusion criteria were defined a priori, and reinforced by specific guidelines for systematic reviews in the agri-food sector, which emphasize the importance of clearly defining the study question and selecting relevant study designs (Sargeant *et al*., 2005).

Studies were selected based on their relevance to at least one of the following dimensions: biodiversity, water use efficiency, carbon cycling, and animal welfare in grazing-based livestock systems.

Table 2 - Inclusion and exclusion Criteria

Domain	Inclusion Criteria	Exclusion Criteria
Topic	Studies evaluating grazing effects on biodiversity, water use, carbon cycle, or animal welfare	Studies not addressing at least one of the four sustainability dimensions
Study type	Articles, Narrative reviews	commentaries, opinion pieces
Publication period	From 2010 to 2025	Published before 2010
Geographic scope	Studies conducted in Europe	Studies not conducted in Europe
Open Acces	Full-text available	Abstract only or inaccessible full text

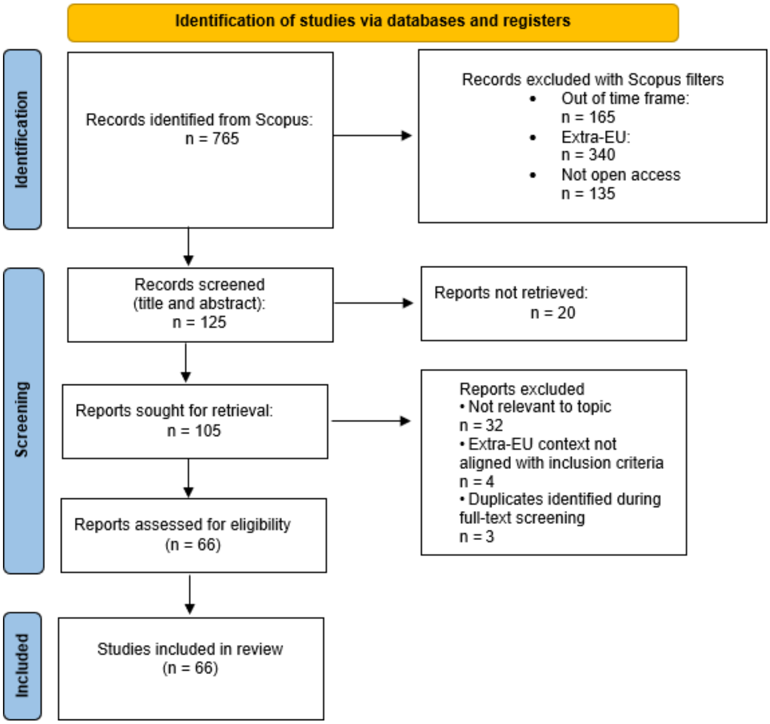
Source: Authors' elaboration.

The initial identification of records was carried out manually via Scopus. Search strings were constructed using combinations of key terms related to the four thematic categories:

- *Pasture grazing and biodiversity.*
- *Pasture grazing and water use.*
- *Pasture grazing and carbon farming.*
- *Pasture grazing and animal welfare.*

The flow diagram representing the systematic selection process for all included studies follows the PRISMA (Preferred Reporting Items for Systematic review and Meta-Analysis Protocols) method (Page *et al.*, 2021). Preliminary exclusion criteria were applied directly on Scopus through filters, including publication date (from 2010 to 2025), availability of full text (open access), and geographic context (with a focus on European studies).

Figure 1 - PRISMA-based Schema



Source: Author's elaboration on base Page M. J. *et al.* BMJ 2021.

The next stage (reports sought for retrieval, n = 105) involved retrieval of all texts and a more careful assessment of methodological appropriateness and thematic relevance. It is worth noting that a small number of duplicate records were identified at this stage (n = 3). This limited overlap was due to the use of a single database (Scopus) and four separate thematic searches (via keywords). Separation by domain initially prevented automatic detection of duplicates, which was resolved during eligibility screening.

3. Results

3.1. *Literature distribution*

Data extracted from the selected studies were synthesised using a narrative approach, given the heterogeneity of study designs, geographical contexts, and methodological approaches. The synthesis was structured thematically along the four main dimensions defined in the research framework: (1) biodiversity, (2) water use efficiency, (3) carbon cycle, and (4) animal welfare. Each study was categorized based on its thematic focus and geographical location, selecting only European studies.

A total of 765 studies were initially retrieved from Scopus after keyword filtering. The thematic distribution highlights a predominant focus on water use (49.4%), followed by biodiversity (29.5%), animal welfare (12.6%), and carbon (8.5%). A temporal analysis reveals a shift in research interest: while the link between environmental dimensions such as grazing and biodiversity or water use has been explored for over a decade, most studies on carbon sequestration and animal welfare are more recent, with over 90% of articles in these categories published after 2010 (Table 3).

Table 3 - Temporal distribution of literature

Thematic Area	No. of Articles	% of Total	Articles 2010-2025	% of Category
Pasture grazing & biodiversity	227	29.5%	184	81%
Pasture grazing & water use	377	49.4%	265	70%
Pasture grazing & carbon farming	65	8.5%	63	96%
Pasture grazing & animal welfare	96	12.6%	88	92%
Total	**765**	**100%**	**598**	**–**

Source: Author's elaboration.

This suggests a growing awareness of the role of pasture-based livestock systems in climate change mitigation and the sustainability of livestock farming.

Another dimension explored was the geographical distribution of the literature (Table 4). Of the 764 studies, only 260 (34%) focused on European countries, revealing a significant knowledge gap related to the four explored dimensions of grazing, particularly in relation to water use and carbon sequestration. Thematic areas such as animal welfare (52.1%) and biodiversity (54.2%) have a relatively larger share of EU-based studies, while water use lags significantly behind (18.3%), despite its relevance in a context of increasing climate variability and water stress in southern Europe.

Table 4 - Geographical distribution of the literature

Thematic Area	No. of Articles	EU Articles	% EU of Total
Pasture grazing & biodiversity	227	123	54.2%
Pasture grazing & water use	377	69	18.3%
Pasture grazing & carbon farming	65	18	27.7%
Pasture grazing & animal welfare	96	50	52.1%
Total	**765**	**260**	**34.0%**

Source: Author's elaboration.

The preliminary evidence emerging from this review highlights the evolving role of grazing systems across multiple sustainability dimensions in the European context. While the environmental role of pasture-based livestock farming has long been acknowledged in terms of biodiversity and water dynamics, emerging challenges such as climate change mitigation, greenhouse gas emissions, and ethical livestock management are gaining increasing attention. However, the geographic and thematic imbalance in the literature suggests a need for greater integration between sustainability dimensions and for enhanced focus on European systems, particularly in water governance and carbon-related practices.

3.2. *Narrative synthesis*

The following narrative synthesis presents the key findings emerging from the selected studies, organized according to the four sustainability dimensions examined in this review. Given the heterogeneity of study designs, geographic contexts, and methodological approaches, results are discussed thematically to highlight recurring patterns, relevant contrasts, and emerging insights. The synthesis focuses on how pasture-based livestock system have been studied in relation to each dimension, offering a comprehensive overview of their environmental and animal welfare implications across different European contexts.

3.2.1. Grazing and biodiversity

Pasture grazing plays a central role in the conservation of biodiversity across European landscapes. Numerous studies confirm that grazing, when properly managed, enhances both plant and habitat diversity, especially in semi-natural and marginal environments.

Moderate grazing intensity, for instance, has been associated with increased plant and pollinator richness (Freschi *et al*., 2015), and with improved habitat heterogeneity in low- input pastures (Tonn *et al*., 2019). In Mediterranean systems, Candel-Pérez *et al.* (2024) and Fracchiolla *et al.* (2017) demonstrate how intensive or unmanaged grazing reduces plant richness, favouring disturbance-tolerant species. By contrast, targeted restoration interventions such as mowing or reseeding (Ponzetta *et al*., 2010; Sitzia *et al*., 2010) have proven effective in reversing biodiversity loss in abandoned grasslands. Similar dynamics emerge in Polish meadows, where grazing influenced species abundance and beetle community composition (Szyszko-Podgórska *et al*., 2024; Czarnecki *et al*., 2015), and in Sweden, where the reintroduction of grazing restored functional invertebrate assemblages (Steiner *et al*., 2016).

Animal biodiversity and habitat structure also benefit from appropriate grazing patterns. Schmitz & Isselstein (2020) and van Klink *et al.* (2016) show that grazing regime, more than species, determines structural diversity and ecosystem function. Dumont *et al.* (2020) found that pasture size altered vegetation patchiness, while Fleurance *et al.* (2016) noted positive insect responses to moderate stocking rates. Furthermore, Wróbel *et al.* (2020) highlight how moderate sheep grazing sustains both plant richness and pastoral value in mountain ecosystems. Landscape-level perspectives reinforce these findings. Plieninger *et al.* (2015) identify wood-pastures as biodiversity hotspots tied to cultural values. In a broader EU context, climate change adds additional complexity Dibari *et al*. (2015) report reduced pasture suitability in the Apennines, threatening grazing-dependent biodiversity. Similarly, Lennartsson & Westin (2023) document how the loss of traditional seasonal grazing affects grassland resilience. At policy level, Roeder *et al*. (2010) and Asheim *et al*. (2020) argue for improved incentives to support pasture-based systems, while Phelps & Kaplan (2017) call for better land-use frameworks integrating biodiversity goals.

Finally, the role of local breeds and traditional practices emerges clearly. Studies from Agradi *et al*. (2023), and Verduna *et al*. (2020) link transhumance and autochthonous livestock to greater landscape heterogeneity and ecological sustainability. Potenza & Fedele (2011) emphasize that well-managed grazing, aligned with agri-environmental rules (e.g. GAEC) of Common Agriculture Policy (CAP), supports floristic richness even in marginal terrains.

3.2.2. Grazing and water use

The management of grazing systems plays a pivotal role in shaping water use efficiency (WUE), with direct implications for soil conservation, hydrological dynamics, and reduced irrigation demand in livestock production. Several studies confirm that that well-managed grazing, such rational grazing, particularly in semi-arid regions, can optimize water use without compromising animal productivity. For instance, Ates *et al*. (2013) showed that deficit irrigation (50–75%) in pasture-based sheep systems improved WUE while maintaining both yield and animal performance.

Beyond water requirements, grazing significantly influences soil structure and hydrological functioning. Moret-Fernández *et al*. (2011) reported that grazing alters the hydro-physical properties of soils, notably reducing infiltration rates and increasing bulk density, particularly in non-gypsiferous substrates. Similarly, Minea *et al*. (2022), observed that small ruminants' grazing intensified surface runoff, reduced infiltration, and increased erosion in hilly and mountainous terrains, ultimately affecting local water balances. Despite such potential risks, appropriately managed grazing can promote hydrological stability and improve resource efficiency. In semi-arid Mediterranean pastures characterized by chalky soils, Moret- Fernández *et al*. (2021) demonstrated that intensive livestock grazing significantly reduced surface water infiltration due to trampling-induced crusting, while having minimal impact on soil matrix water retention. In contrast, moderate grazing intensity did not negatively affect soil hydraulic properties, indicating its potential suitability as a sustainable management strategy for soil conservation under these specific drought conditions.

From a livestock behavior standpoint, Tsiobani *et al.* (2023) observed that water availability influences buffalo spatial distribution in Mediterranean pasture systems, as animals tend to cluster near water points, an effect with notable implications for grazing patterns and landscape pressure. Pasture-based systems also contribute to reducing overall water consumption in meat production. According to Dillon *et al.* (2018), in recent decades, permanent grasslands in Europe have declined by 14%, leading to an increased reliance on irrigated crops for livestock feed. Comparative analyses of production systems indicate that water use to produce 1 kg of beef is 30-50% lower in grazing-based systems compared to intensive systems. Furthermore, grazing contributes to improved soil moisture and reduced evaporation, thereby decreasing the need for artificial irrigation. In support of this, modeling by Simionesei e*t al.* (2018) on Portuguese montado systems confirmed that irrigation can increase biomass yield, but also raised transpiration, suggesting that grazing management needs to balance productivity with water use. Grazed pasture, being the lowest-cost and rain-fed feed source in temperate Europe, enhances the self-sufficiency and environmental sustainability of dairy systems by reducing reliance on externally irrigated feed crops and buffering against water-related constraints (Hennessy *et al.*, 2020). Finally, Bernués *et al.* (2011) emphasized that sustainable grazing practices contribute to water security by reducing irrigation needs and improving the resilience of Mediterranean farming systems. Extending the grazing season from 252 to 300 days has been shown to decrease the need for irrigation water and improve the forage self-sufficiency of livestock farms.

3.2.3. Grazing and Carbon Cycle

A growing body of empirical and theoretical research demonstrates that well-managed pasture-based systems play a significant role in enhancing carbon sequestration and mitigating greenhouse gas (GHG) emissions in a variety of agroecological contexts. Tölgyesi *et al.* (2023) highlight the multifunctional benefits of sparse trees in temperate tree pastures in Hungary and Romania, where they achieved increased carbon stocks and biodiversity without compromising livestock productivity. These findings are consistent with those of Smetanová *et al.* (2019), who report that traditional extensive grazing in the Czech Republic maintains higher soil carbon levels than abandoned lands, resulting in benefits for biodiversity and landscape conservation. Complementary findings from Poland show that rotational grazing of deer improves forage quality and alters plant chemical composition (Kulik *et al.*, 2023), while also modulating soil chemical and enzymatic properties (Futa *et al.*, 2024), albeit with a reduction in total organic carbon during the winter. Studies focusing on carbon footprints also point to the benefits of grazing systems. Morais *et al.* (2018) report lower greenhouse gas emissions per kg of product in extensive grazing systems using local breeds, from the Azores showing a carbon footprint of 0.83 kg CO_2e/kg of milk, among the lowest in Europe. Morais *et al.* (2025) further highlight the variability of GHG emissions (15-124 kg CO_2e/100 g protein), noting that pasture-based systems consistently outperform in terms of emissions reductions. Hessle and Danielsson (2024) estimate that the restoration of semi-natural grasslands in Sweden can be achieved through favourable conservation status, strategic reductions in livestock density rates, and partial mowing. Carswell *et al.* (2024) report that reseeding pastures with legume-rich swards improves nitrogen use efficiency in beef and sheep systems, without significantly increasing productivity, while also enhancing carbon sequestration in established swards.

O'Brien *et al.* (2016) provide life-cycle assessment evidence that moderate intensification improves carbon efficiency in Irish sheep systems, although the results are highly dependent on assumptions regarding soil carbon sequestration. At the system design level, Barron *et al.* (2021) propose an integrated assessment framework for pasture-based dairy sheep farming systems in Spain, identifying soil carbon sequestration as a key sustainability indicator. Meanwhile, Pauler *et al.* (2023) demonstrate that carbon storage in mountain pastures is influenced by topography and climate (e.g., slope, temperature), with higher forage productivity correlating with greater carbon storage but reduced biodiversity, highlighting key ecosystem trade-offs. Recent work by Zhu *et al.* (2023) also confirms that high-resolution satellite data combined with eddy covariance flux towers can reliably extrapolate carbon fluxes at the field scale in managed European grazing systems, offering promising tools to monitor and assess pasture-based climate mitigation strategies.

3.2.4. Grazing and Animal Welfare

Hesselmann *et al.* (2025) demonstrate that allowing dairy cows to graze on multispecies swards supports natural foraging behavior and individual dietary self-selection, enhancing welfare through behavioral autonomy. Similarly, Molle *et al.* (2022) emphasize the role of planned rotational grazing (PTG) in supporting welfare by improving mobility, milk quality, and promoting natural behaviors. The traditional knowledge of shepherds, as documented by Rivera *et al.* (2022), also contributes to welfare, with the use of over 200 medicinal plants for animal care in transhumant systems. The influence of grazing intensity and management was assessed by Crossley *et al.* (2022), who reported only minor welfare differences between treatment groups, with better locomotor conditions and comfort observed in cows with longer grazing periods. Likewise, Crump *et al.* (2019) found that overnight pasture access improved cow welfare by enhancing lying time, activity, and behavioral synchrony. However, temporary indoor confinement, as shown by Enriquez-Hidalgo *et al.* (2018), negatively affected lying behavior and locomotion, especially in Jersey cows, while O'Driscoll *et al.* (2019) observed reduced lying behavior due to limited pasture allowance. Environmental enrichment and infrastructure also play a key role. Delaby *et al.* (2020) highlight how hedgerows and wooded areas provide shade and shelter, improving thermal comfort and reducing disease risk. Turini *et al.* (2025) confirms this by showing that access to water and shade during hot periods mitigates haemoconcentration and metabolic stress in sheep, compared to animals exposed to harsher conditions. Technological solutions were explored by Marchegiani *et al.* (2025), who report that Precision Livestock Farming (PLF) tools enhance welfare via real-time health monitoring and optimized grazing management, although adoption remains limited. Similarly, Bosona & Gebresenbet (2021) suggest that mobile automated milking systems can promote cow-calf contact and reduce stress in pasture-based setups. McCormick & Stokes (2023) note that GPS collars, if well-managed, offer benefits in extensive systems despite potential welfare concerns related to invisible or fluctuating boundaries. Behavior-based metrics are gaining ground but still face challenges. Aubé *et al.* (2023) found that avoidance distance at pasture (ADP) is not yet a reliable individual-level indicator for human-animal relationship assessment. O'Leary *et al.* (2020) observed that mild and moderate lameness in cows did not consistently correlate with behaviour patterns, suggesting limitations in current accelerometery-based detection. Research in other species reinforces the welfare potential of pasture-based systems. Battini *et al.* (2021) adapted the AWIN (Welfare Indicators Network) protocol for goats and identified generally good welfare, despite concerns about body condition and water access. Agradi *et al.* (2023) and Niero *et al.* (2022) confirm that well-managed alpine and summer pastures support animal health and milk quality without negative impacts on udder health. Welfare implications of landscape use were examined by Larraz *et al.* (2024) who used GPS data to analyze habitat preferences of free-grazing sheep, suggesting better alignment of resource distribution with animal behavior. In a similar ecological context, Rutherford *et al.* (2021) highlight that incorporating surplus male dairy calves into pasture-based beef production systems represents a more welfare-friendly alternative to practices such as long- distance export. Strand *et al.* (2019) highlight a concret concern in outfield systems, predation by large carnivores increases stress, injury, and mortality among sheep, suggesting that welfare benefits of grazing systems are context dependent. Grodkowski *et al.* (2023) further emphasize that organic certification alone does not always guarantee superior welfare, especially when compared to well-managed conventional systems.

Finally, Ripamonti *et al.* (2024) report no significant welfare differences between cattle raised in silvopastoral and open pasture systems, as evidenced by stable cortisol levels. Avondo *et al.* (2013) link pasture-based feeding to enriched milk and cheese quality, with bioactive compounds that not only enhance product value but may also support animal health.

4. Discussion

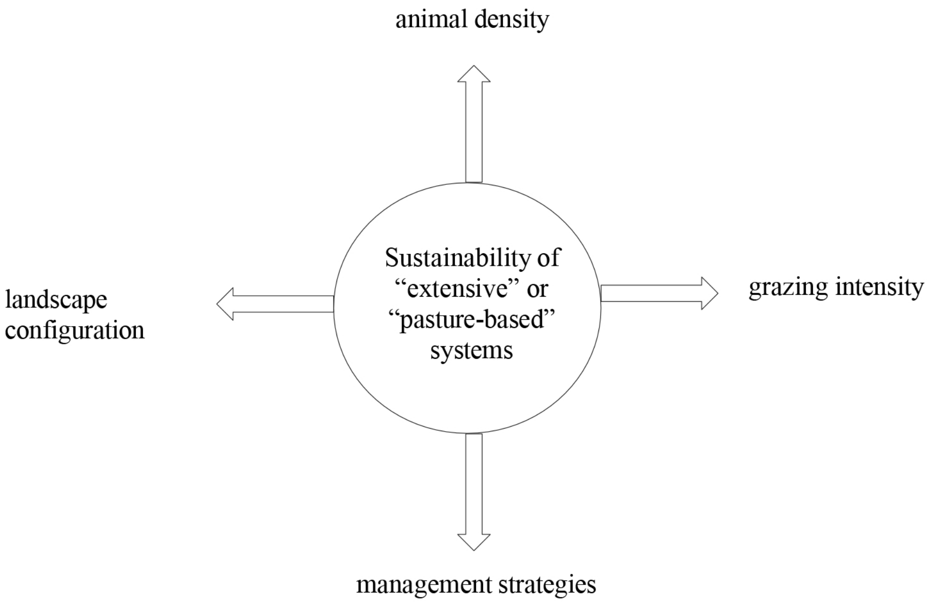
While this review focused on the environmental and animal welfare impacts of pasture-based livestock systems in Europe, it is essential to contextualize the findings within a broader sustainability framework, including economic viability and global perspectives.

Evidence from non-European studies, in line with this review, highlights substantial variability in sustainability outcomes even among comparable grazing systems. As Broom (2021) argues, the mere classification of a system as "extensive" or "pasture-based" does not ensure sustainability; rather, outcomes depend on context-specific factors, including grazing pressure, animal density, pasture design, and management strategies. For instance, the same rotational grazing model may lead to biodiversity gains in one context and neutral or even negative effects in another, depending on how it is implemented (Ripoll-Bosch *et al.*, 2013). This calls for adaptive and locally informed grazing strategies rather than blanket recommendations.

Moreover, although our review restricted data inclusion to European studies, relevant global literature offers valuable insights that reinforce and expand upon our conclusions. For example, silvopastoral systems in Latin America have demonstrated that integrating tree cover into grazing landscapes can yield positive outcomes for biodiversity, productivity, and animal welfare (Broom *et al.*, 2013; Broom, 2017). These systems offer functionally similar models to Mediterranean agroforestry and could inspire design adaptations in Europe's southern regions. Additionally, Broom (2022) proposes the use of sustainability scoring to assess the balance of trade-offs across environmental, animal, and economic dimensions a tool potentially adaptable to European contexts.

Crucially, the economic sustainability of grazing systems must be further emphasized. Although often overlooked in environmental reviews, financial viability is essential for long-term adoption by farmers. Studies by Bernués *et al.* (2014) highlight that pasture-based systems contribute to rural livelihoods and resilience, especially in marginal areas where alternative agricultural models are less feasible. These systems also tend to show lower dependence on external inputs and greater resilience to market volatility, due to self-sufficiency in forage and reduced feed costs (Toro-Mujica *et al.*, 2015; Ripoll-Bosch *et al.*, 2013). Furthermore, as FAO (Chará *et al.*, 2019) notes, despite lower short-term productivity, these systems offer robust long-term benefits for food security and socio-economic stability under climate stress.

Figure 2 - Factors influencing the sustainability of extensive or pasture-based system



Source: Author's elaboration.

Conclusions

This review substantially confirms the contribution of well-managed grazing systems to global agro-environmental sustainability. Properly managed livestock farming systems based on pasture can offer significant benefits across all key sustainability dimensions: environmental, economic, climatic and animal welfare. The analysed scientific evidence indicates that practices such as rotational grazing, holistic management, agro-livestock integration, and adapting grazing practices to local ecological and climatic conditions can improve water use efficiency (WUE), optimise hydrological dynamics, increase organic carbon sequestration in the soil, and preserve biodiversity without compromising livestock performance. In particular, adopting strategies such as deficit irrigation in pastoral systems in semi-arid regions has been shown to significantly reduce water consumption while maintaining comparable yields, thereby contributing to the ecological resilience of these areas. Conversely, the structure and management of pastures have a profound influence on the physical, chemical and enzymatic properties of the soil, thus confirming the interdependence between livestock practices, soil health and environmental quality. Furthermore, recent research highlights the importance of breed-specific grazing behaviour, grazing time distribution and vegetative structure in determining animal performance and the overall sustainability of systems. Another important factor is animal welfare. Extensive grazing encourages natural behaviour and improves feeding autonomy, promoting better physical and behavioural health in line with the principles of the One Health framework. In particular, in low-input farming, animals play a central role as efficient converters of non- edible plant biomass into animal-based food. For instance, dairy cows transform grass into milk, supporting the circular use of resources and contributing to food security. Increasing the proportion of grazed forage in the annual feed plan is associated with lower production costs, higher profitability, and greater farm resilience. However, these benefits do not occur automatically and depend on several factors, including grazing intensity, infrastructure quality, soil and climate conditions, landscape, and political and institutional support. Integrating traditional knowledge with advanced technological tools, such as sensors, GPS tracking, decision support systems and precision farming technologies, offers concrete prospects for adaptive pasture management in response to climate change and increasing environmental variability. These emerging tools offer promising opportunities to improve the monitoring and optimisation of interactions between animals, vegetation and soil. However, there are still obstacles to adoption and specific challenges, including water scarcity, predation risks and land fragmentation, which require contextualised, multisectoral solutions. In light of this evidence, it is clear that extensive livestock systems can represent a strategic ecological safeguard for landscape regeneration, soil fertility improvement and climate change mitigation, rather than being a threat to the environment. Future agricultural development strategies should therefore recognise the functional role of grazing within an integrated ecosystem approach, promoting targeted support policies and investments in transdisciplinary research, as well as coordinated actions at local, national and global levels. Only through such a systemic, multi-level vision will it be possible to exploit the full regenerative potential of pastoral systems and contribute concretely to achieving global climate, environmental and socio-economic objectives.

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