

Perspective

# Sustainability Assessment of Pasture-Based Dairy Sheep Systems: A Multidisciplinary and Multiscale Approach

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**Abstract:** This article describes a novel methodological approach for the integrated sustainability assessment of pasture-based dairy sheep systems. Most studies on livestock system sustainability focus on animal production, farm profitability, and mitigation strategies of greenhouse gas emissions. However, recent research indicates that pasture-based livestock farming also contributes positively to rural areas, and the associated increase in plant diversity promotes ecosystem functioning and services in natural and managed grasslands. Likewise, little attention has focused on how pasture-based livestock systems affect soil carbon changes, biodiversity, and ecotoxicity. Furthermore, the quality and safety of food products, particularly sheep milk and cheese, and socioeconomic issues such as cultural heritage and consumer behavior are often neglected in livestock system sustainability assessments. To improve the analysis of sustainability and adaptation strategies of livestock systems, we suggest a holistic approach that integrates indicators from diverse disciplines with complementary methods and models capable of capturing the complexity of these systems at multiple scales. A multidisciplinary perspective generates new indicators to identify critical trade-offs and synergies related to the resilience of dairy sheep livestock systems. A multiscale approach provides insights on the effects of socioeconomic and environmental changes associated with current dairy sheep grazing systems across multiple scales. The combined approach will facilitate the development and progressive implementation of novel management strategies needed to adapt pasture-based dairy sheep farms to changing conditions under future socioeconomic and environmental scenarios.

**Keywords:** dairy sheep livestock; grazing management; multidisciplinary indicators; multiscale dimension; sustainability assessment

## 1. Introduction

Dairy sheep systems generate employment and other opportunities for rural populations in many countries [1]. These systems often rely on traditional grazing management linked to specific territories and local breeds, and include on-farm milk processing and distribution of dairy products through local marketing channels [2]. Although pasture-based sheep production occurs in temperate climate zones, it often takes place in mountains and other areas with harsh conditions (extreme temperature and low rainfall) and highly seasonal production [3]. Dairy sheep offer advantages over dairy cows in terms of adaptability to climate and orographic areas [4]. Moreover, low-input farming systems and dairy

products are often protected under internationally recognized labels. Despite this, dairy sheep systems, particularly grazing-based systems, face significant challenges related to the need for improved milk production, the innovation and introduction of new technologies, and the development of new, wide-scale market niches for products [5].

In recent decades, traditional pasture-based sheep raising has experienced changes, including the introduction of more productive non-native breeds, the easing of trade in production inputs and processed products, and an increased demand for processed products [6,7]. As dairy farms become less connected locally and more dependent on external inputs, farms are more vulnerable and have reduced resilience to unfavorable market situations [8]. In many countries, the ovine sector has also experienced significant flock reduction because of socioeconomic changes: many farmers have abandoned pasture-based dairy sheep farming due to a lack of generational succession, or have transitioned to more intensive approaches [9].

Intensive livestock activity has been criticized for its impact on the environment and animal welfare. In contrast, pasture-based extensive livestock systems contribute not only to local employment and income generation, but also to culture and landscape heritage, gastronomy, and tourism in traditional sheep-grazing areas [1]. However, there is a debate around whether intensive or extensive livestock perform better in terms of greenhouse gas emissions [5]. A recent study observed a wide variability in the environmental footprints of dairy farms as affected primarily by climate and soil characteristics, and secondarily by farm intensification degree [10]. Other studies indicate that grazing systems contribute to biodiversity and do actually sequester carbon in amounts that partially, or in well-managed cases entirely, compensate for the emissions of these systems [5,11]. In addition, these grazing systems contribute essentially to the maintenance of high nature value (HNV) farmlands, being environmentally friendly production systems. They are usually small farms located in areas less favorable for agriculture, such as remote and mountainous regions. Although HNV farmlands have been integrated within the common agricultural policy (CAP) structure and have been recognized as a priority objective, the practical implementation of actions is hindered because of a lack of methodological tools for assessing and delineating these HNV farmlands [12]. An integrative assessment methodology that combines multiple indicators, as proposed in this article, would help to better allocate CAP aids from an environmental perspective.

Despite significant progress in the investigation of socioecological systems [13,14] and the integration of multiple fields of knowledge in the study of extensive grazing systems [6,9], further research is needed to assess the sustainability of these systems across scales [15]. The sustainability of an extensive grazing system should be analyzed considering the multiple scales of the food system in which it operates, i.e., from the biochemical and ecological processes occurring on the soil to the biomes, the animal physiological processes, the dairy activities in the farm, to the socioeconomic processes in local communities, the food industry, and local and international markets [16]. The integration of these aspects becomes even more necessary especially in dairy sheep systems, where the management is extensive or semi-extensive and predominate rustic autochthonous breeds, and fluctuating space-time dynamics (transhumant herds) are involved.

There are several works analyzing the sustainability of interregional food systems at different scales (i.e., national and regional impacts of international trade and external dependency of food systems) [16], while others remain analyzing livestock systems at a single scale (see references in Table 1). However, there are no studies simultaneously characterizing local livestock systems, analyzing their impacts on local ecosystem and their contribution to food and socioeconomic systems. This article aims at filling this gap by proposing a methodological framework that combines primary data collection at farm and local level, the characterization of farm typologies, and the evaluation of future scenarios across scales and dimensions, in order to evaluate the ecological, socioeconomic, and food quality performance and external dependency of pasture-based livestock systems. Therefore, the purpose of the proposed methodological framework is to capture trade-offs

and synergies among multiple dimensions and scales of analysis to support decision-making processes.

## 2. Multidisciplinary Sustainability Indicators

Livestock sustainability assessment methodologies tend to focus on environmental and economic dimensions [17], limiting their ability to cover the diversity of functions, goods, and services provided by diverse systems. A more diverse set of indicators could capture the multiple contributions of livestock systems from an interdisciplinary perspective [18]. Recent studies have reviewed the trade-offs and synergies between pasture-based livestock farming and other ecosystem services, demonstrating that innovative methods of analysis are needed to unravel the linkages between grazing systems and other ecosystem services [19].

Provisioning (food quantity and quality), environmental quality (biodiversity, landscape heterogeneity, soil and water quality), rural vitality (employment, rural dynamism), and culture (gastronomy, landscape heritage) have been proposed as main categories of goods and services derived from livestock systems [19]. There is a consensus that sustainable livestock systems should provide a net farm income that supports an acceptable standard of living for farmers, minimize environmental impacts (e.g., greenhouse gas emissions mitigation, waste treatment, recycling), produce safe and nutritious foods, promote a good level of animal welfare, meet social expectations (gender issues, employment standards, heritage landscapes), and enhance or maintain high biodiversity standards [19,20]. Hence, an evaluation of these systems should consider concurrently the ecological, social, and economic dimensions of sustainability.

Two holistic indicator-based frameworks for livestock sustainability assessment include these multidimensionality and multifunctionality aspects. The sustainability assessment of farming and the environment framework includes the three classical pillars of sustainability and is structured on content-based principles, criteria, and indicators [21]. The framework for assessing the sustainability of natural resource management systems is organized on the attributes of productivity, stability, reliability, resilience, adaptability, equity, and self-reliance [22]. However, the sustainability of livestock systems also depends on many, often interrelated, factors that differ among farming systems and change over time. Thus, a thorough analysis of the evolving factors that affect livestock system sustainability over time must include a dynamic perspective [9]. Table 1 presents information from 34 studies published over the last 15 years on the sustainability of dairy and meat livestock (sheep, goats, cows) systems at different locations. The table shows the methodology used as well as the assessment dimensions, attributes, and indicators. The environmental dimension of sustainability is by far the most studied, with economic and social dimensions included to a lesser extent. The outputs are very different in terms of the number and type of attributes and indicators used; however, carbon footprint is the prevalent indicator in environmental sustainability studies compared to more than 100 potential indicators in the multidimensional studies (Table 1).

**Table 1.** Selected articles published over the last 15 years on the sustainability of different dairy and meat livestock systems (sheep, goat, and cow) in different locations. The table shows the scaling, methodology, dimensions, and indicators used for the sustainability assessment.

Animal Species	Livestock Production	Location	Methodology	Dimensions	Indicators	Scaling	References
goat	dairy	Spain	MCE	EC + SOC + EN	6 attributes (productivity, stability, reliability, resilience, adaptability, equity, self-reliance) and 44 indicators	farm level	[23]
		Spain	LCA	EN	carbon footprint	cradle to farm gate	[24]

Table 1. Cont.

Animal Species	Livestock Production	Location	Methodology	Dimensions	Indicators	Scaling	References
		New Zealand	LCA	EN	carbon footprint and carbon sequestration	cradle to farm gate	[25]
		Spain	LCA	EN	cradle to farm gate	cradle to farm gate	[26]
		Italy	LCA	EN	11 impact categories including climate change	cradle to farm gate	[27]
sheep	dairy	Spain	MCE	EC + SOC + EN	7 attributes (productivity, stability, reliability, resilience, adaptability, equity, self-reliance) and 35 indicators	farm level	[28]
		Spain	MCE	EC + SOC + EN	20 attributes and 112 indicators	farm level	[29]
		Spain	LCA	EN	carbon footprint and carbon sequestration	cradle to farm gate	[30]
		Italy	LCA	EN	17 impact categories including climate change	cradle to farm gate	[31]
		Italy	LCA	EN	11 impact categories including climate change and ecotoxicity	cradle to farm gate	[32]
		Spain	LCA	EN	carbon footprint and carbon sequestration	cradle to farm gate	[33]
	meat	Spain	MCE	EC + SOC + EN	7 attributes (productivity, stability, reliability, resilience, adaptability, equity, self-reliance) and 37 indicators	farm level	[9]
		Australia	LCA	EN	nutrient balance and soil acidification	farm level	[34]
		Spain	LCA	EN	carbon footprint	cradle to farm gate	[35]
		Ireland	LCA	EN	carbon footprint and carbon sequestration, nutrient balance, soil acidification, eutrophication, land use efficiency	cradle to farm gate	[36]
cow	dairy	Colombia	MCE	EC + SOC + EN	17 indicators (4 economic, 5 social, and 8 biophysical)	farm level	[37]
		The Netherlands	MCE	EC + SOC	63 indicators regarding animal welfare	farm level	[38]
		Brazil	MCE	EC + SOC + EN	116 indicators regarding governance, environmental integrity, economic resilience, and social well-being	supply chain	[39]

Table 1. Cont.

Animal Species	Livestock Production	Location	Methodology	Dimensions	Indicators	Scaling	References
		Algeria	MCE	EC + SOC + EN	42 indicators regarding agroecology, socio-economy, and territory	farm level	[40]
		Germany	LCA	EN	8 impact categories including climate change, ecotoxicity, and biodiversity	cradle to farm gate	[41]
		Spain	LCA	EN	stratospheric ozone depletion, acidification, eutrophication, photo-oxidant formation, and depletion of abiotic resources	cradle to farm gate	[42]
		Italy	LCA	EN	global warming, ozone depletion, photochemical oxidation, soil acidification, eutrophication, energy resources, wastes	cradle to farm gate	[43]
		Ethiopia	LCA	EN	global warming, land use, and fossil energy use	cradle to farm gate	[44]
		Ireland	SLCA	SOC	workers, local community, society, value chain actors	cradle to farm gate	[45]
	meat	Spain	MCE	EC + SOC + EN	41 indicators grouped by 5 categories	farm level	[46]
		Indonesia	MCE	EC + SOC + EN	116 indicators regarding governance, environmental integrity, economic resilience, and social well-being	farm level	[47]
		Argentina	MCE	EC + SOC	economic, energetic, and productive indicators	farm level	[48]
		Cameroon	MCE	EC + SOC + EN	14 indicators (social, economic, and environmental categories)	regional level	[49]
		United States of America	LCA	EN	climate change, eutrophication, acidification, human health, damage to ecosystem diversity, damage to resource availability	cradle to farm gate	[50]
		Uruguay	LCA	EN	carbon footprint and sequestration, fossil energy, soil erosion, nutrient balance, pesticide ecotoxicity, and biodiversity	cradle to farm gate	[51]

Table 1. Cont.

Animal Species	Livestock Production	Location	Methodology	Dimensions	Indicators	Scaling	References
		Thailand	LCA	EN	climate change, soil acidification, eutrophication, and energy consumption	cradle to farm gate	[52]
		Italy	LCA	EN	carbon footprint and carbon sequestration	cradle to farm gate	[53]
		United States of America	LCA	EN	water emission, energy demand, land use, acidification, photochemical ozone, global warming, abiotic depletion	cradle to farm gate	[54]
		Mexico	SLCA	EC + SOC	18 impact subcategories within 5 major categories: human rights, working conditions, health, socioeconomic impact	farm level	[55]

MCE: multi-criteria evaluation, LCA: life cycle assessment, and SLCA: social life cycle assessment.

Several main methodologies were used in the research reviewed in Table 1. The life cycle assessment is the main tool for the environmental assessment of livestock systems, whereas the social life cycle assessment and multi-criteria evaluation are applied when other socioeconomic attributes or dimensions are integrated into the analysis. Little attention has been paid to soil carbon changes, biodiversity, and ecotoxicity attributed to livestock systems and their degree of intensification [56,57]. However, research has shown that pasture-based livestock farming contributes positively to rural areas, and that increasing plant diversity can promote ecosystem functioning (multifunctionality), stability, and services in natural and managed grasslands [58].

The quality and safety of food products and social issues such as cultural heritage and consumer behavior have not been considered important indicators to assess the sustainability of agri-food systems. The nutritional and sensory qualities of foods, in particular those of animal origin such as meat and dairy products, are strongly influenced by animal diet and management practices [59]. Higher nutritional quality is associated with meat and dairy products from pasture-based sheep systems [60–62]. The relationship between consumer behavior and the sustainability of food production systems has been investigated only rarely [63]. One exception is a recent study developed by Bernués et al. [64] that explored the social preferences for ecosystem services in European agro-ecosystems including environmental, biodiversity, and food quality indicators.

In short, a multidisciplinary perspective allows the generation of new socioeconomic and biophysical indicators that can identify critical trade-offs (e.g., among environmental impacts, animal welfare, good working conditions and economic profitability) and synergies (e.g., among biodiversity conservation, maintenance of cultural heritage, and the production of high quality food) in livestock production systems [6]. These indicators can be decisive in sustainability assessments, particularly for pasture-based systems, and can point to adaptation strategies to deal with environmental and socioeconomic changes. Although some multidisciplinary assessment frameworks exist, they need to be expanded to include new dimensions such as food quality and human and animal health-related factors.

### 3. Multiscale Dimension

A major challenge for sustainability analysis is the inclusion of multiple scales in assessing the metabolism of socioeconomic systems and its relation with the surrounding

ecosystems. By social metabolism we refer to the processes of material and energy transformation that are necessary for the existence of societies [15,65], i.e., the transformation of inflows of energy and materials to the outflows of waste and degraded energy that are needed for production and reproduction. When analyzing complex systems operating at different scales (e.g., socioeconomic systems operating at individual, household, community, and societal levels), changes generating benefits at one scale of an analysis may not be so beneficial at another level. For instance, lowering milk prices at the farm level may increase added value at the whole dairy production level but pose a risk to farm-level viability. Likewise, changing the analysis scale can capture emergent properties relevant to sustainability analysis. For instance, a grazing area may be considered homogeneous at the farm level but may be part of a diverse landscape mosaic fundamental for biodiversity conservation at a landscape level.

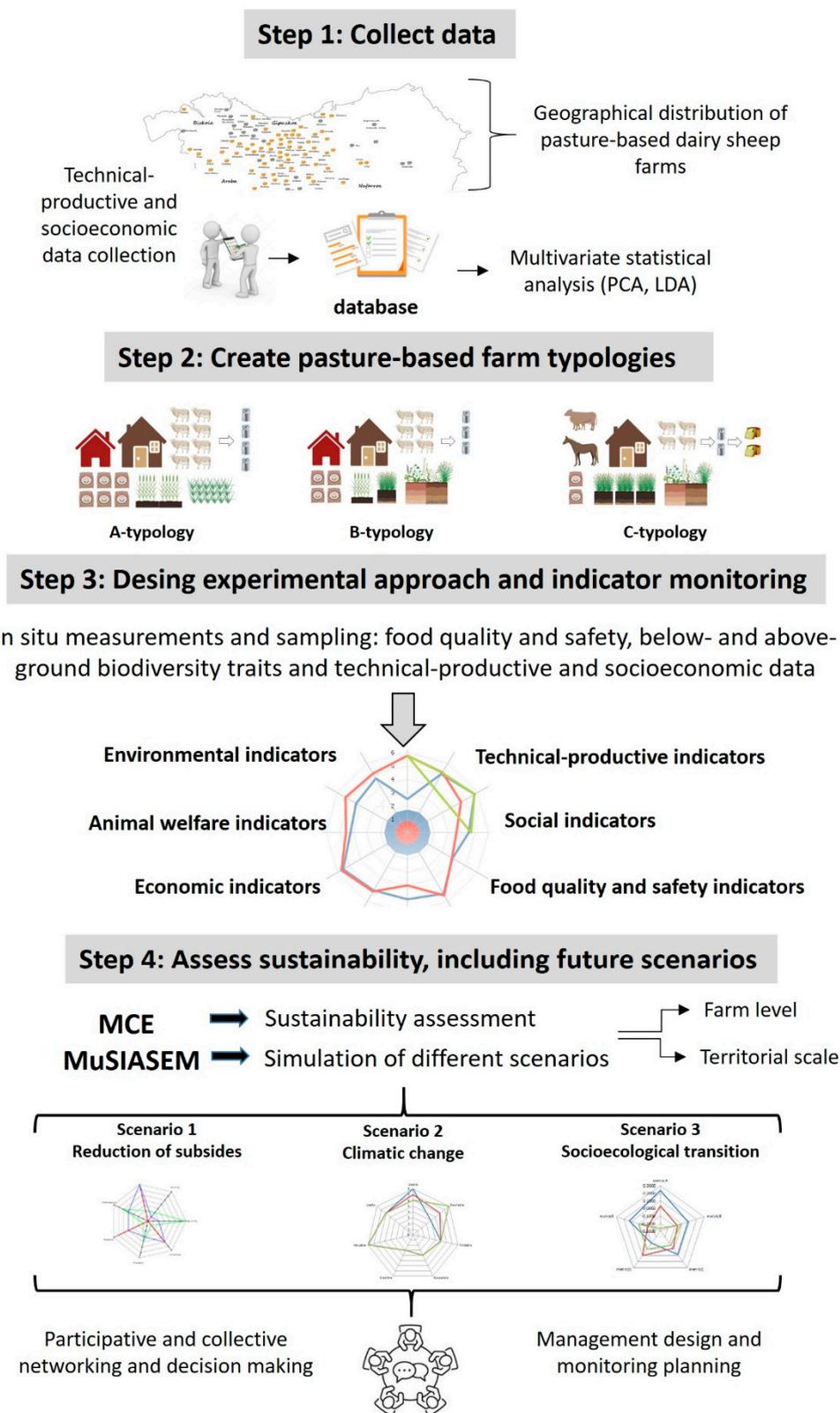
In livestock sustainability studies, the farm is typically the main level of analysis, regardless of the sustainability dimensions used (Table 1). Models can analyze the economic and ecological sustainability of livestock systems at the farm scale [66], providing a deep understanding of the livestock system and enabling proposed improvements adapted to the farm [67]. However, disregarding other levels of analysis hinders understanding of multiscale relations, such as feedback loops across scales, non-linearity, and the existence of emergent properties.

Together with multidisciplinary indicators, a multiscale dimension that includes farm-level and greater scales offers deep knowledge of the consequences that socioeconomic and environmental changes pose to current dairy sheep-grazing systems. Scales can be ecological (plot, ecosystem, biome/landscape), jurisdictional (farm, village, county, province, nation), or sectoral (farm, dairy sector, food system), but all scales used for the analysis should be coherent with the purpose of the analysis [68].

The multiscale integrated analysis of societal and ecosystem metabolism provides an accounting framework for a quantitative analysis of socioecological systems at multiple scales. It enables the analysis of socioecological systems combining two perspectives: (i) an external view to assess the feasibility of the metabolic pattern (i.e., the profile of energy and material transformations) with regard to external constraints (i.e., those aspects outside the human control) such as resource availability and sink capacity of the surrounding ecosystems, and (ii) an internal view (i.e., those aspects under human control) to assess the viability of the metabolic pattern with regard to internal constraints such as technical and/or economic issues [15,68]. The ability to integrate quantitative assessments across dimensions and scales makes this analytical framework particularly suited for sustainability analyses such as the nexus between food, energy, water and land uses, and rural development [69].

#### **4. Exploring a Systematic Methodology for Assessing the Sustainability of Pasture-Based Dairy Sheep Systems**

The integrated sustainability assessment of dairy sheep pasture-based livestock systems, as well as the simulation of future socio-economic and environmental scenarios, requires a systematic methodological scheme (Figure 1).



**Figure 1.** Systematic methodological scheme for the assessment of the sustainability of pasture-based dairy sheep systems. PCA, principal component analysis; LDA, linear discriminant analysis; MCE, multi-criteria evaluation; MuSIASEM, multiscale integrated analysis of societal and ecosystem metabolism.

#### 4.1. Step 1: Collect Data

As the starting point, data are collected from management and control centers, farmers' associations, and direct farm-level interviews guided by a questionnaire. The aim is to identify farm traits related to technical-productive parameters (e.g., farm dimension and facilities, flock size, farm grassland surface and infrastructure, percentage of rented lands, annual production of milk, cheese, and lambs), management variables (e.g., grazing calendar, flock short transhumance, pasture type, feed and fodder composition, manure, antibiotic usage, animal welfare parameters), and socioeconomic data (e.g., income from product sales, net margins, full range of costs, subsidies, profitability, jobs, time use, gender-related issues, other socioeconomic inputs). The extent of data to be collected is determined by the issues relevant to the study. These are defined by the research team, but it is also important to include the opinion of main stakeholders when defining which questions are key to answer. At present, animal welfare parameters are critical in assessing farm sustainability, and should also be included and analyzed according to international criteria [70]. Parameters based on farm environmental conditions and animal handling and those that identify problems in the animal (appearance, behavior, clinical signs) should be recorded in farms. These parameters record in situ the state of the animals in terms of feeding (body condition, state of feces, water availability and quality), and health (mortality and diseases records, injuries, lameness, udder condition, eye or nasal discharges, respiratory quality, wool quality). Farmhouse environmental conditions (temperature, airstream, ventilation), animal handling (available lying area per animal in housed or in controlled pastured slots animals, shade/shelter availability in extensive management, bedding quality, animal comfort, stressed animals, hooves condition, animal cleanliness), and facilities (feeders, straw feeders, water availability and drinkers) should be also recorded. Close collaboration with farmers and farmers' associations during this step will create a network and enable reliable and accurate data collection.

#### 4.2. Step 2: Create Pasture-Based Farm Typologies

A typology is the simplification of real entities to a representation, based on expected relations between the components of the entity, which gives rise to an expected behavior [68]. Following previous studies [71–75], we propose to develop the following process to define farm typologies. First, the farm is considered the basic unit to develop farm typologies because it is the real unit of operation where productive decisions are made. Then, the first step in this process is to develop a qualitative conceptual framework that establishes a hypothesis about the structure and performance of farms, according to farmer characteristics and production aims [71,72]. This conceptual framework is translated into a set of variables capturing the information necessary to validate the hypothesis. In other words, the set of variables is the operative expression of the conceptual framework [71]. The hypothesis and the variables used to classify farms would be based on both researchers' theoretical understanding of the subject under study and local knowledge (e.g., local technicians, rural officers, park rangers, farmers) [72,73].

Then comes the definition of the variables to be used for the classification. These variables should be internal of the farm. External conditions, such as location or market conditions, are necessary to understand the development and spatial distribution of farms but should not be used to classify farms. According to Kostrowicki [74], three types of variables should be considered: (i) social characteristics of the farm (i.e., who is the farmer that makes decisions) and the scale of operation, (ii) operational characteristics (i.e., how the farm is operated, according to the available labor and capital inputs), and (iii) production characteristics (i.e., what and how much is produced, and for what purposes). These would include, for instance, indicators on the size of the farm, the level of capitalization, labor structure, production system, level of intensification, land ownership, and income structure, among others [71]. In other words, the selected variables should describe the performance of farms, in terms of what they do and how and why they do what they do with the available resources.

After selecting variables, a factorial analysis (e.g., principal component analysis) takes place to reduce the dimensionality of the data, obtaining a set of factors (i.e., linear combinations from original variables) explaining the data variability and retaining those variables that mostly contribute to the variance of the data. Then, a cluster analysis is performed using the main factors (Kaiser criterion) obtained in the previous step. We propose an agglomerative hierarchical clustering process using Ward's minimum distance. In this process, farms are progressively grouped according to their similarities. At each step, the number of clusters decreases and the within-cluster variance increases. Therefore, it becomes necessary to determine an adequate number of clusters for the further analysis. The overall objective would be obtaining typologies that result in a minimum variability within types and a maximum variability between types. The resulting farm typologies can be interpreted according to the principal component analysis results [72]. However, most importantly, the resulting farm typologies should serve for the purpose of the analysis [75] and be based on the researchers' experience and the knowledge acquired through empirical observations [76]. Finally, a non-parametric Kruskal–Wallis test followed by a Bonferroni multiple comparison test is applied to check differences among the farm types for each of the indicators considered [77]. It should be noted that the sample size of farm typologies would be determined by the purpose of the analysis and by the statistical requirements to have significant results. In this sense, a common rule is that at least five observations in each group are required to obtain significant *p*-values in the multi comparison tests.

#### 4.3. Step 3: Design Experimental Approach and Indicator Monitoring

The purpose of this step is twofold. First, once typologies are defined, it is necessary to characterize the environmental conditions surrounding farms, especially those related to semi-natural grasslands and meadows managed by the farmer. For this purpose, in situ measurements of abiotic factors (e.g., climatic variables, soil compaction, soil water content and temperature), as well as biotic factors (e.g., soil microbial activity and composition, mesofauna, floristic composition, roots and aboveground functional traits) should be recorded in selected farms applying suitable experimental designs. The objective of these measurements is to provide the essential inputs of each farm type to be able to estimate environmental parameters such as greenhouse gas emissions and fertility and soil health, taking into account the particularities of each farm type. In addition, this will allow analyzing the relationships between these parameters and the outputs of the farm (production and quality of milk, cheese and meat), and detecting the most important differences between typologies. Because of the effort involved, researchers must select a limited, representative number of farms for each farm typology. The selection of these farms is based on their proximity to the typology's average.

Second, quantitative measurements must be made with respect to the quality and safety of dairy products. Sampling of bulk raw milk and cheeses produced on the selected farms should occur at different times in the lactation period and be adapted to farmers' management practices. Food quality and safety parameters should be determined in the laboratory. Nutritional quality traits for dairy sheep products from pasture-based farms are gross composition, fatty acid profile, and tocopherol and mineral contents. Food safety parameters should include checking for pathogenic microorganisms such as *Listeria monocytogenes*, *Salmonella* and *Staphylococcus aureus*, and somatic cells; total aerobic counts; and biogenic amine content (in cheese). Additionally, because of the impact of antibiotic use on the presence of antibiotic-resistance genes in animal foods, it is relevant to determine antibiotic residues in cheeses from farms affected by infections. The analysis of terpenoids in milk and cheese can be used as a grazing management chemical marker, which is relevant for pastured-based systems [78]. In addition to farm-level data, the quantitative analysis should include data addressing consumer perception and preference regarding products from differing production systems. Information about a food product creates expectations concerning its sensory properties and acceptability. Studying the impact of information is particularly relevant in the case of food production systems strongly related

to sustainability as pastured-based dairy systems. Therefore, the target is to assess the impact of information about the sustainability of the production systems on the sensory acceptance of dairy products, and to determine if this influence varies according to the awareness of the consumer regarding sustainability. The methodology of the consumer behavior study should be focused on the consumer acceptability degree of dairy product samples using a labeled affective magnitude scale [79]. Data generated in this step will complement that collected in step 2, including information pertaining to the landscape level and the quality of food produced.

#### 4.4. Step 4: Assess Sustainability, Including under Future Scenarios

The multidimensional and complex nature of sustainability assessments requires multiple, simultaneous analyses from diverse disciplines, as well as an awareness of the strengths and targets of each methodology. Step 4 involves two consecutive phases: (i) applying analyses and models at the farm level, and (ii) integrating approaches for sustainability assessment and the evaluation of future scenarios at multiple scales.

##### 4.4.1. Analysis at Farm Level

The farm level is the appropriate scale for evaluating options to optimize technical, socioeconomic, and productive performance because livestock management decisions occur at this level. First, farm typologies are characterized according to a set of multidimensional indicators. Relevant indicators are defined based on the quantitative story telling approach [80]. Following [77,81], the process starts by identifying relevant narratives about the issue at stake. In this case, it is the sustainability of pasture-based dairy sheep systems. Then, it follows the identification of the essential elements used within narratives to describe the dairy systems, the attributes, which are then translated into categories formalized in terms of a specific measurement process, the indicators. To assess the indicators we use the multiscale integrated analysis of societal and ecosystem metabolism accounting framework based on Georgescu–Roegen’s fund-flow model [15]. The information generated in steps 1 and 3 is used to value the different indicators.

##### 4.4.2. Integrated Assessment of Future Scenarios at Multiple Scales

Next, the overall metabolic profile of each dairy sheep farm typology and the associated sustainable management strategies under alternative future scenarios are assessed. This would entail changes in the metabolic profile of farm typologies leading to the emergence of new farm typologies or the change of the share of each farm typology in the study area, which are to be estimated based on the research team’s knowledge. For instance, future scenarios can be related to: (i) changes in animal diets, simulating those based on foods with low social, health, animal welfare, and environmental externalities; (ii) environmental changes that allow the sector to be better integrated into the circular bio-economy through recycling of nutrients and energy from livestock waste, and use of recycled food waste; (iii) changes in animal welfare and health, simulating conditions in which animals are treated with respect to satisfy ethical and consumer demands, and under which food safety, emerging diseases, and antimicrobial resistance are minimized through the adoption of best productive practices and capacities to respond to threats; and (iv) changes in socioeconomic conditions (e.g., market shocks, improved supply chains) or policy options (e.g., different subsidy and agro-environmental schemes).

Given the multiple factors that can intervene in the definition of alternative scenarios, it is of key importance to ensure that the definition and validation of scenarios is performed in close collaboration with key stakeholders and representatives of all affected parties. It is also important to notice that future scenarios are considered here as a prospective tool to explore the potential effects of possible changing situations. Then, by aggregating the performance of farm typologies according to their participation in the possible future situation, the socioeconomic and biophysical performance of dairy production systems can be assessed at upper scales (e.g., local, regional, national) as well as by their aggregate impacts on

the surrounding environment. The aggregation rules of the multiscale integrated analysis of societal and ecosystem metabolism accounting framework [15] are followed for this analysis (for applications, see references [69,82]. Next, a multi-criteria structure (i.e., a matrix with dairy farm typologies evaluated under a set of multidimensional indicators expressed in their original units of measurement) can be used to identify and analyze trade-offs among environmental, socioeconomic, technical-productive, and food quality and safety dimensions of dairy sheep systems (see reference [83] for a recent review on multicriteria decision analysis methods for agri-food research).

## 5. Opportunities and Challenges

The multidisciplinary and multiscale approach we present will offer relevant information for public administration and socioeconomic sectors at local, regional, and international levels, and can assist decision-makers to support more efficient management of farms and rural areas. It can be used to diagnose the critical aspects of livestock systems performance using a set of biophysical and socioeconomic indicators and to anticipate potential changes across scales by exploring and assessing possible scenarios. More precisely, it contributes to (i) evaluating potential trade-offs among multiple dimensions (e.g., ecological and economic) and scales (e.g., local and regional); (ii) identifying “winners” and “losers” under each management option or scenario (e.g., farmers, representatives from industry, government agencies, etc.); (iii) assessing the effectiveness and efficiency of alternative policies (e.g., subsidies, technological changes that are able to shape the behavior of the system under study); and (iv) designing sustainable pathways based on the previous outputs. Hence, in comparison to other conventional approaches (see Table 1), this approach is a holistic endeavor to address complex interactions across dimensions and scales in the analysis of livestock systems. For instance, we could address multiple ecological gains and losses derived from dietary changes of livestock, and the socioeconomic and environmental implications of extensification/intensification processes at farm and ecosystem levels. Likewise, we would be able to assess the impact of global changes at local and farm scales, e.g., the impact of changes in global fuel prices or changes in the CAP priorities on the performance at farm level. Most interestingly, the analysis across dimensions and scales using multiscale integrated analysis of societal and ecosystem metabolism enables the analyst to assess the biophysical feasibility of future scenarios; that is, the compatibility of the system with the processes outside human control (e.g., what are the limits of local ecosystems (pastures) to livestock extensification? What are the limits of water extraction to support livestock intensification?). Moreover, at the same time, we can evaluate the socioeconomic viability of future scenarios [84], that is, the compatibility of processes under human control (e.g., is there enough available human labor to cover the requirements of livestock extensification?). This approach will also facilitate the progressive implementation of resilient management strategies to adapt pasture-based dairy sheep farms to changing socioeconomic and environmental conditions. Outputs derived from multidisciplinary and multiscale perspectives are expected to drive the creation of collective decision-making networks involving all stakeholders in the livestock system and corresponding food chain (Figure 1).

The holistic characterization of livestock farms and grazing systems using food quality, economic, social, and environmental indicators enables decision-makers to identify and support more sustainable practices. Notwithstanding, this process is not free from difficulties, which include: (i) identifying the relevant stakeholders and involving them in the whole evaluation process, (ii) defining adequate indicators, and (iii) the great efforts needed to gather the primary information that has to be taken into account. We consider that the identification of key social actors can only be achieved by implementing an open, inclusive, and transparent participatory process. Power relations may affect the degree of participation of social actors and the results of participatory processes. Therefore, special attention should be put in the mechanisms used to incorporate the perspectives of different social actors. In this regard, triangulation of sources of information is advisable

(combining, e.g., in-depth interviews, workshops, focus groups, text analysis of technical and political documents and public declarations). The participatory approach must also account for the potential influence of powerful actors and create spaces to freely express ideas and opinions [85]. When the perspectives and concerns of relevant social actors have been identified, the definition of adequate indicators can be performed following the methodology used by [77]. It should be noticed that there are no fixed rules or guidelines to assist analysts in the process of translating social perspectives into indicators. In fact, this process depends more on the art and experience of the analyst than on science [86]. This is why a multi/interdisciplinary work is required to define adequate indicators under different dimensions. The efforts of primary data collection can be alleviated through the creation of collaborative networks with farmers, agencies, and technicians working on the ground. Furthermore, triangulation of methods (such as participant observations, time-use workshops, activity logs, in-depth interviews) can be used to reduce dependency on a single data collection method and increase their effectiveness. Finally, producing information that is relevant and useful for the involved social actors can be a good way to motivate social actors to participate and collaborate (e.g., defining the objectives of the analysis between the research team and the participants).

The livestock sector faces significant challenges associated with changing global conditions, multiple stakeholder interests, and new social demands (e.g., greater animal welfare, reduced antibiotic use, minimized environmental impacts, and healthier, chemical-free dairy foods that have excellent sensory properties). We hope that the framework proposed in this article can contribute in search of sustainable management pathways that ensure the survival of pasture-based dairy sheep systems and satisfy current socioecological demands of society.

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