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Dairy farming sustainability: development of an integrated multi-dimensional framework

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Sustainability assessment in dairy farming requires approaches capable of simultaneously capturing environmental, social, and economic factors. This pilot study tested the applicability of a multi-dimensional framework for dairy farm sustainability assessment, applied to a set of case-study farms. Agroecosystem services (AES) were evaluated using the Agroecosystem Service Capacity Index, adapted to intensive production context; plant biodiversity was assessed through the Shannon diversity index; socio-economic aspects were analyzed following the guidelines of the Public Goods Tool, and environmental impacts were quantified through Life Cycle Assessment (LCA). Grassland and semi-natural vegetation provided the highest contributions to biodiversity and regulating services, whereas arable land mainly contributed to provisioning services. Arable land and grassland emerged as the main drivers of AES capacity. Dairy efficiency was associated with improved economic performance without reducing landscape and heritage value while social capital and water management emerged as critical aspects across farms. Environmental impacts expressed per hectare were positively related to AES provision, whereas the opposite trend was observed when impacts were expressed per unit of milk. Results suggest that careful management of marginal areas and grassland may support biodiversity and ecosystem regulating services without compromising productivity or profitability. Although based on a limited number of case-study farms, this study demonstrates the feasibility of an integrated methodological approach for jointly analyzing environmental, social, and ecosystem-service indicators at the farm level, enabling cross-dimensional comparison and providing a basis for future validation and decision-support applications.

KEYWORDS
biodiversity, dairy farming systems, ecosystem services, life cycle assessment, socio-economic dimensions

1 Introduction

Interest in environmental sustainability has grown steadily in recent years. Among the sectors receiving the most attention is livestock production, especially ruminant systems, which are often subject to public criticism.

At the same time, ruminant farms play a key role in rural landscapes and local economies. Grassland-based farming systems help preserve cultural landscapes and food heritage, while contributing to air and water quality, climate regulation, and biodiversity conservation (Dumont et al., 2019). Moreover, farms contribute to provisioning services (Augstburger et al., 2019), particularly in intensive systems. Conversely, livestock systems generate disservices and negative externalities such as habitat loss, nutrient leaching and runoff, GHG emissions, and other environmental impacts (Shackleton et al., 2016; Biagetti et al.,2023; Dumont et al., 2019).

The main challenge is therefore to identify management practices capable of reconciling the different pillars of sustainability: environmental, social, productive, and economic (Wattiaux, 2023).

The environmental impact of agricultural products is widely assessed through the Life Cycle Assessment (LCA) approach, an internationally recognized methodology regulated by ISO standards and broadly accepted at the global level. LCA evaluates environmental impacts in relation to production efficiency and therefore follows a framework typical of environmental economics (Biagetti et al., 2023). However, the LCA approach mainly captures negative environmental impacts and provides only a partial assessment of sustainability due to methodological limitations (Cruz-Rivero et al., 2025). In particular, ecosystem services, such as biodiversity, are often not integrated into LCA, especially in livestock systems (Sooriya Patabendige and Uddin, 2025).

Among the services provided by farms, those related to the environment, land and society are generally considered under the broader category of Ecosystem Services (ES) i.e., the benefits people obtain from ecosystems. These include provisioning services, such as food and water; regulating services, such as regulation of floods, drought, land degradation, and disease; supporting services, such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other non-material benefits (Millennium Ecosystem Assessment, 2005).

Human demands for ecosystems and the need for institutional support are expected to increase in the coming years, driven by rising consumption of biological and physical resources, as well as escalating impacts on ecosystems and the services they provide (Millennium Ecosystem Assessment, 2005; Zabala et al., 2021). Consequently, the analysis of ecosystem services (ES) has become a key component in the sustainability assessment of policy options and technological solutions (Othoniel et al., 2016).

The classical approach to ES has focused on economic valuation, traditionally conducted at territorial scale to inform environmental policies (Ignatyeva et al., 2022). However, this top-down perspective may fail to capture the specific contributions of agricultural systems to ecosystem functions, as it does not explicitly account for farm-level management practices, land-use heterogeneity, and marginal or semi-natural elements within farms.

An alternative approach involves narrowing the scale of analysis to the farm level, thus enabling direct assessment of Agroecosystem Services (AES) and comparisons across farms. In this context, the farm is considered an "agroecosystem": an anthropized system shaped and managed by human activity (Zabala et al., 2021).

Agroecosystem Services (AES) are determined by the interaction between ecosystem functions and human agricultural practices, with both positive and negative effects, scale effects, trade-offs and synergies (Liu et al., 2022). Most agroecosystem components are shaped, either totally or partly, by human management, while some natural components such as shrubs, herbivores, predators, microorganisms, and other organisms are retained. These components play an important role in the maintenance of the productivity and stability of agroecosystems. Therefore, the agroecosystem can be seen as a semi-natural ecosystem that has characteristics of both natural and artificial ecosystems and aims to achieve agricultural production under the joint control of humans and nature (Liu et al., 2022).

Several methods exist to quantify ES. A widely applied matrix-based approach uses land cover classes as the basis for assigning and scoring services. Indicators can then be defined and quantified through biophysical measurements (Burkhard et al., 2009; Campagne et al., 2020).

To have a comprehensive understanding of sustainability, it is essential to evaluate not only environmental, but also social and economic pillars. Understanding the relationship between different aspects of sustainability and the factors that influence them represents both a challenge and an opportunity. Sustainable agriculture is an "integrated system of plant and animal production practices having a site-specific application that will, over the long term: (a) satisfy human food and fiber needs; (b) enhance environmental quality; (c) make efficient use of non-renewable and on-farm resources integrating appropriate natural biological cycles and controls; (d) sustain the economic viability of farm operations; and (e) enhance the quality of life for farmers and society as a whole" (Velten et al., 2015).

Many studies aim to integrate the different dimensions of the sustainability pillars into comprehensive assessment tools. Among these, the DEXi software is a multi-attribute decision-making tool based on qualitative attributes expressed through categorical scales (e.g., "low", "medium", "high"). This model integrates farm management practices, environmental impacts derived from LCA assessments, and economic and social indicators (Wilfart et al., 2023). However, as noted by the authors, a key limitation of this approach is the need for large and detailed datasets, as well as the inclusion of panel data analyzes, which restricts its applicability at a broader scale.

Another integrative approach was developed by Hörtenhuber et al. (2025), combining LCA impact categories with animal health indicators and economic outcomes. The resulting set of indicators was used to cluster dairy farms, enabling both benchmarking and a more in-depth exploration of sustainability patterns across different farm types. A major limitation of this tool is the absence of social sustainability dimensions and the lack of a standardized scoring system for overall farm performance.

Despite these advances, there is still a lack of integrated, operational frameworks capable of jointly assessing environmental impacts, agroecosystem services, and socio-economic dimensions at the farm level under real production conditions.

In this study, sustainability is addressed through an integrated assessment of environmental, economic, and social dimensions. Agroecosystem services are considered as functional components of the environmental dimension, capturing ecosystem capacity and management-related effects not represented by Life Cycle Assessment, while productive performance is treated as a key driver influencing all dimensions rather than as an independent sustainability dimension. The objective of this pilot study was to test the applicability of objective and quantifiable methodologies for assessing dairy farm sustainability through an integrated analysis of environmental impacts, agroecosystem services, and socio-economic dimensions. By applying the framework to four case-study farms in Northern Italy, the research aimed to evaluate the feasibility of a methodological approach that can support future applications in different farming contexts.

2 Materials and methods

This study was conducted on four dairy farms in Lombardy, Northern Italy, selected to represent differences in size and management practices, all located in the region. Three farms operated under intensive systems (without pasture, using silages and concentrates in the ration), while one was managed according to organic rules. In all farms, lactating cows were kept indoors with cubicles year-round. The limited number of farms reflects the pilot and exploratory nature of the study, which aimed to test the applicability of an integrated framework combining environmental, social, and economic dimensions with agroecosystem service assessment.

2.1 Evaluation of agroecosystem services

Agroecosystem services were evaluated using the Agroecosystem Service Capacity Index (ASCI; Augstburger et al., 2019), which is based on a land-cover-class approach, adapted to the intensive production system (Appendix A). The adaptation was required to ensure the applicability of the index to indoor-based dairy systems characterized by high productivity and limited grazing. The adaptation of the original ASCI framework to intensive dairy systems was based on literature evidence and expert-based adjustments to reflect high-input production conditions.

For each land cover class (LCC) the Agroecosystem Service Capacity (ASC) was calculated according to the following equation:

$$ASC_i = (\frac{S_i + N_i}{2}) * A_i$$

where A is the share of a specific land cover class i within the farm Utilized Agricultural Area (UAA), while N and S represent, respectively, the number of services provided and the strength of service provision associated with land cover class i. The four LCC categories considered in this study are:

1. Structures: all buildings belonging to the farm, serving as farm residence and labor and management buildings, animal housing, milking facilities, feed and nutrition structures, water supply systems, waste management systems and their infrastructure (paddocks, roadways and loading dock, power supply and backup generators).
2. Natural vegetation: indigenous or naturally occurring plants that grow without direct human intervention. This includes grass, shrubs, trees, and other plants native to the region or naturally adapted. In a farm, natural vegetation can exist in uncultivated areas such as field margins, pastures, riverbanks, forest patches, and hedgerows.
3. Semi-natural vegetation: plant communities that developed under a mix of natural growth and human influence. These areas are not entirely wild but have not been completely cultivated. They often arise from past land use (like grazing) and are maintained by low-intensity practices or natural regeneration.
4. Grassland: crops that do not require replanting after each harvest and continue to produce yields for several years (permanent and semi-permanent meadows and pastures). These crops are typically grown to provide long-term sources of feed for dairy animals or to support the overall sustainability of the farm.
5. Arable crops: crops that are grown on land that is plowed or tilled regularly. These are usually annual crops, meaning they complete their life cycle in one growing season and must be replanted each year, with the exception of some forage species such as *Medicago sativa*, which is perennial but included in crop rotation and replanted after some years.

The steps developed to assess the ASC were mapping, questionnaire and biodiversity assessment.

2.1.1 Mapping

Farm dossiers (legally required documents, DPR 503, 1999) and cadastral maps were used for mapping the different areas of the farm. The dossier divided the farm's surface in LCC and the areas of these classes were identified with arable crops, grassland, natural and semi-natural areas, structures (building, shelters, houses). Land cover classes were identified and mapped using Geographic Information System (GIS) data.

2.1.2 Questionnaire

A questionnaire was administered to farmers to gather information on: farm characteristics, management of animals and land cover classes. The first part of the questionnaire focused on general farm data: milk production, herd size, UAA, feed rations, purchased and self-produced feed, subsidies, market channels, secondary activities, implementation of recommended practices (Augstburger et al, 2019), educational and social activities.

The second part included specific questions to assign to each LCC the number and the strength of service they could provide based on: yield, seed production, timber production, fuel and energy production, water and irrigation, signs of wind or water erosion, soil fertility, tillage and soil processing, crop varieties.

An informed consent to participate in the study was obtained from all the farmers. Data were stored anonymously, in agreement with the EU General Data Protection Regulation (GDPR).

2.1.3 Biodiversity assessment

Vegetation biodiversity was assessed on each farm using the Shannon Index (Dušek and Popelková, 2017) calculated for each land cover class (LCC).

$$\text{ShI} = -\sum_{i=1}^{m} \text{Pi} \log \text{Pi}$$

Where:

m = number of the categories studied (e.g. land cover class).

P_i = proportion of i-th floristic category in the total area: $\frac{B_i}{\sum_{i=1}^{m} B_i}$

B_i = surface area of i-th category.

For each land cover class, a set of sampling areas were identified from the georeferenced land use maps. Different sampling method were adopted according to the land cover class: herbaceous cover, fields or homogeneous vegetation (arable crops, grassland as permanent and semi-permanent meadows, uncultivated areas without shrubs), vegetation belts, edge areas, identified as linear elements characterized by mixed vegetation, trees and/or shrubs and/or grasses and forests, tree-planted areas with or without cutting and management plans. For all LCCs, only one sampling campaign was carried out at the beginning of the season, in late spring 2023 (from April to June) during the growing season, in order to identify the largest number of species present; in natural state before any human environmental perturbance (e.g. grass cutting grazing). This single-season sampling reflects the exploratory nature of the study and does not capture inter-annual variability. Sampling effort was standardized across farms and land cover classes to ensure comparability of biodiversity estimates.

2.1.3.1 Herbaceous cover

A 1 m^2 square was sampled at three locations along the diagonal of the field: at the beginning, middle, and end; the number of individuals for each species present within the sampling square was counted. The value for the biodiversity estimate was the average of the three squares.

2.1.3.2 Vegetation strips

All trees present and shrubs (for each species) within the land cover class were counted. Additionally, a 1 m^2 square was sampled at three locations (at the beginning of the area, in the middle and at the end) to assess the herbaceous cover. An estimate of the total number of individuals of the herbaceous species (from the average of the three sampled squares) and the total number of tree species was used for the biodiversity calculation.

2.1.3.3 Forests

Two 10 x 10 m squares were sampled and the individuals for each species present were counted. The average value was used to calculate biodiversity.

2.1.4 Agroecosystem service capacity index

Collected data were used to assign scores (1-5) to four service categories: supporting services (biodiversity), provisioning (food crops, wild foods, livestock, fodder, seed, timber, wood fuel, biochemical medicine, fertilizers and soil improvers, energy, freshwater), regulating (local climate regulation, erosion regulation, nutrient regulation, water regulation, pollination, biological control), and cultural (knowledge systems, analyzed at farm level, and cultural heritage and diversity, analyzed at land cover class level). For each category relevant services were identified and corresponding indices were defined based on scientific literature, national reference values, and expert-based adjustments to reflect intensive dairy conditions Scores were assigned using predefined thresholds (Appendix A). To reduce subjectivity, scoring criteria were defined *a priori* and consistently applied across all farms.

Quantitative and qualitative (score-based) indices were selected for each agroecosystem service, calibrated to capture variability among intensive dairy farms.

All indices, including those derived from literature and those newly created, are described in Appendix A which provides detailed scoring methods and references, to ensure transparency and reproducibility. The scores assigned to each LCC were arranged in a matrix (Augstburger et al, 2019) for the computation of the Agroecosystem Service Capacity (ASC), considering the area occupied, the number of provided services, and the strength of these services of each LCC. The ASC was calculated according the following the formula:

$$ASC = \left\{\left[(number\ of\ services\ provided\ \times\ 5)/total\ number\ of\ services\right] + \left[\textstyle\sum_{n=1}^{i}(AES\ score_i/AES_1^i)/2)\right]\right\} \times \%\, LCC_i\ area$$

The sum ASCI for each farm was calculated as the sum of ASC values across all LCCs:

$$ASCI = \sum ASC_i$$

2.1.5 Evaluation of social and economic indices

Indices to monitor social sustainability and economic performance were developed using data collected through questionnaires. Both quantitative and qualitative information were collected from farmers to assess the quality of life and services they can access and social and economic benefits the farm provides to society. The macro-categories included: economic performance (income and costs), food security (in terms of food/feed supply), social capital (job offer and employment), landscape and heritage (historical value and harmony with the environment), resilience (in terms of actual and future survival) and water management (in terms of use and efficiency of water use). Each category was composed by different declarations or indices (Qualitative and quantitative) to which it was assigned a score from 1 to 5, the average value was the final score of the social macro-category.

The evaluation was carried out following the guidelines of the Public Goods tool (PG tool; Gerrard et al., 2011), adapted to the intensive farm context, through the inclusion of additional questions and indicators and the selection of the most representative relation between farms and territory integration of the farm in the specific territory aimed at capturing the relationship between farms and their territorial context (Appendix B).

TABLE 1 Farm characteristics and land distribution.

	Unit	Farm 1	Farm 2	Farm 3	Farm 4
Cows[a]	*(n)*	160	91	504	154
Individual milk[b]	*(kg FPCM/d)*	35.5	30.5	29.4	16.2
Milk yield	*(t FPCM/ha)*	37.7	13.9	19.6	7.61
Dairy Efficiency[c]	*index*	1.32	1.23	1.2	0.85
Feed self-sufficiency[d]	*(%)*	53.3	42.8	57.3	88.6
Total area	*(ha)*	66	51	290	159
UAA[e]	*(ha)*	48	58	270	134
LSU/UAA[f]		5.58	3.45	3.5	2.12
Arable land	*(%)*	79	88	53	42
Grassland[g]	*(%)*	8	0	40	55
Semi-natural[g]	*(%)*	3	6	4	2
Natural[g]	*(%)*	4	0	0	0
Structures[g]	*(%)*	6	5	4	1

a = lactating cows.
b = Fat and Protein Corrected Milk (FPCM)/d assuming 305-day lactation.
c = kg FPCM per kg dry matter intake (DMI).
d = Percentage of self-produced feeds.
e = Utilized Agricultural Area.
f = Livestock Units per UAA.
g= Grassland, >1 year (e.g., permanent meadows, lucerne).
g = Land cover classes.

2.1.6 Environmental impact

The assessment of environmental impacts of milk production was performed through LCA method considering climate change, land use and land use change, eutrophication, fossil resource use, and water use. Inventory data, such as herd, feed rations composition and amount of purchased and self-produced feed, were obtained from the questionnaire.

The functional unit (FU) was 1 kg of Fat and Protein Corrected Milk (FPCM) calculated following International Dairy Federation (2010) formula:

$$FPCM\left(\frac{kg}{yr}\right) = production\left(\frac{kg}{yr}\right) \times (0.1226 \times fat\,\% + 0.0776 \times true\ \ protein\,\% + 0.2534)$$

Allocation between milk and meat was performed by using a physical method (International Dairy Federation, 2010).

Impacts were also expressed per unit of farm area (1 m^2) to enable comparison between production efficiency and land-based environmental pressures.

System boundaries were set from cradle to farm gate. On-farm emissions were calculated according to (IPCC guidelines 2019a, b) with more detailed information available in Rota Graziosi et al. (2022). The emissions related to off-farm activities (e.g., purchased feed inputs) were modelled using background data from Ecoinvent V3.8,(2021) and Agri-footprint V6(2022) databases.

Direct LUC was included in the assessment of soybean meal impact as reported by the Agri-Footprint database (Blonk Consultants, 2022). Life cycle impact assessment was performed with Simapro software by using Environmental Footprint 3.1 V1.01. Differences between biogenic and fossil methane were taken into account.

Selected impact categories were included in the integrated framework based on their relevance for dairy production systems, their sensitivity to management practices, and data availability. Due to the exploratory nature of the study, uncertainty analysis was not performed, and results should be interpreted as indicative.

2.1.7 Interaction among the different dimensions of sustainability

In order to provide evidence on the interrelationship among the different sustainability dimensions, an observational scoring system was applied to selected farm-level variables. A five-point scale (1 - 5) where 1 represents the lowest and 5 the highest performance, was used to harmonize variables expressed in different units and enable comparative analysis, using the formula below.

$$6 - [1 + (x - min) \times (5 - 1)]/(max - min)$$

The variables included: the ASCI index that synthesized the AES; the average of PGtool scores as an indication of economic and social sustainability; climate change impact per unit of milk; climate change and climate change for land use change and eutrophication impacts expressed per unit of area, and production efficiency indicators (milk production and dairy efficiency). This approach allowed cross-farm comparison of integrated sustainability performance and the exploratory identification of potential trade-offs and synergies among sustainability dimensions, which should be interpreted as preliminary patterns requiring further validation.

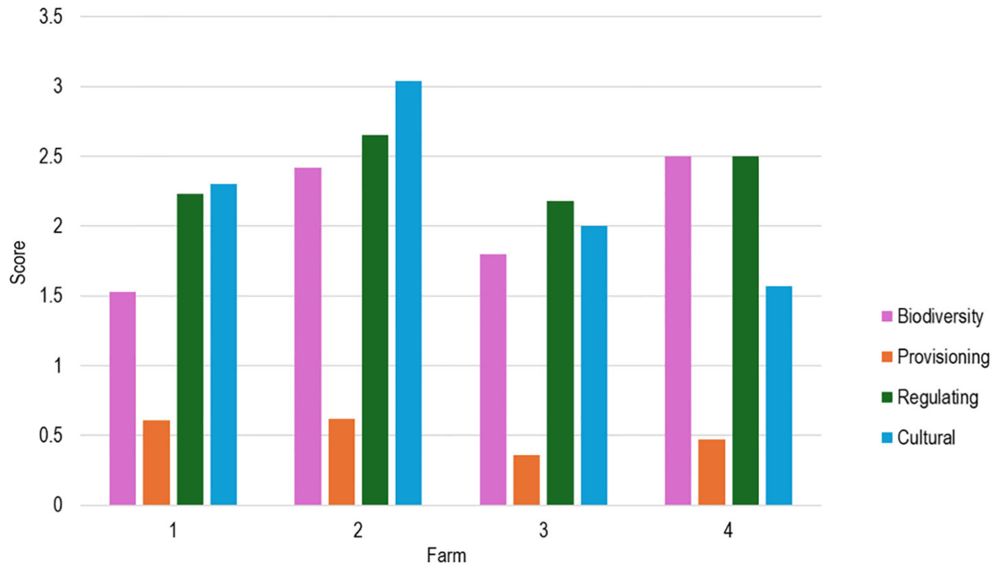

FIGURE 1
Average scores of agroecosystem service categories (biodiversity, provisioning services, regulating services, cultural services) for each analyzed farm.

3 Results

Three farms were managed as high-input indoor systems (without pasture, based on silages and concentrates), while the organic farm, although also keeping lactating cows indoors year-round, allowed dry cows to graze and, thanks to its larger land availability, provided a forage-rich ration compared with the other farms. All four farms relied on substantial external inputs such as purchased feed, labor, and energy. Table 1 summarizes the main structural, productive, and land-use characteristics of the four case-study farms, highlighting variability in herd size, land availability, and stocking intensity that characterizes the analyzed systems. On average, the farms housed 227 ± 187 lactating cows, producing 27 ± 7 kg/d per cow of FPCM, indicating marked heterogeneity among farms. The total farm area was on average 142 ± 110 ha, with 128 ± 102 ha of UAA, conforming a wide variability in farm size and land availability. All results are based on descriptive and observational analysis.

3.1 Agroecosystem services

The average scores for the four service categories (biodiversity, provisioning, regulating, and cultural) are shown in Figure 1. The score represents the average value of the services provided by each LCC within a farm, grouped by service category. These scores indicate the contribution of different service categories provided

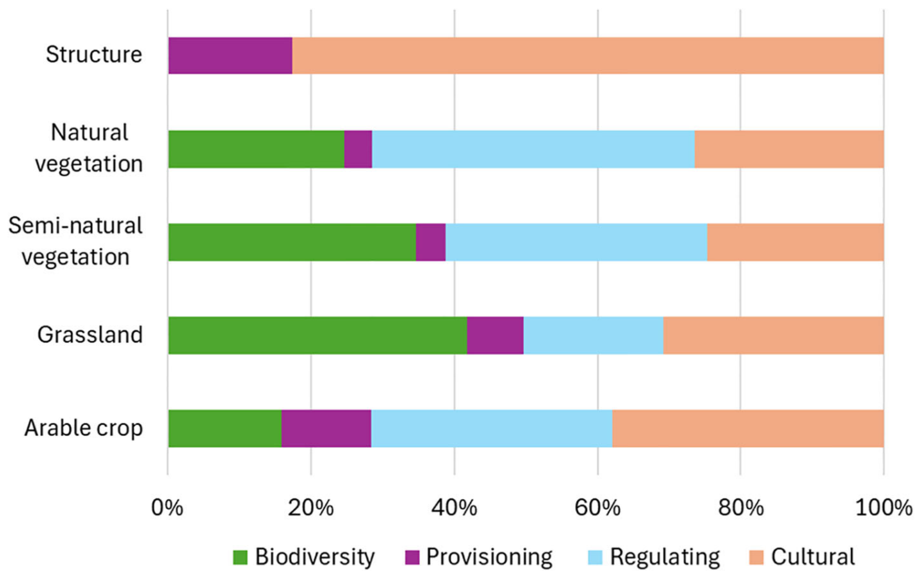

FIGURE 2
Contribution of each land cover class to agroecosystem services.

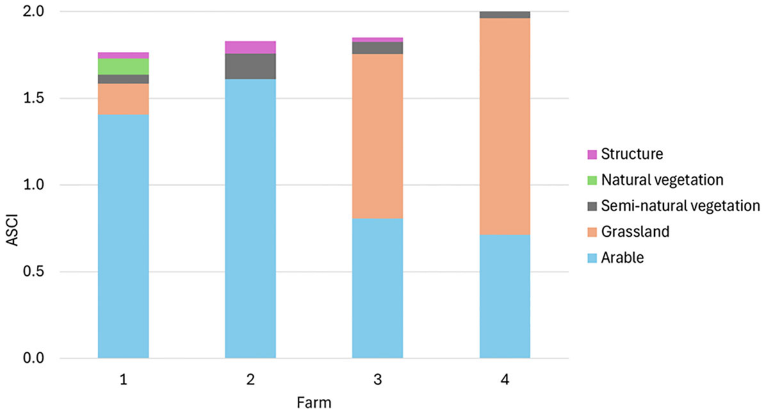

FIGURE 3
Agroecosystem capacity index (ASCI) and its composition in terms of land cover class contributions of analyzed farms.

by each farm, expressed in absolute values (i.e., without weighting by land cover class area) and therefore reflect the intrinsic capacity of each land cover class to provide services rather than their quantitative contribution at farm scale.

Farm 2 had the highest score for cultural and regulating services, while Farm 1 and 2 exhibited the highest values for provisioning services. Farm 4 showed the highest biodiversity service score. These differences reflect contrasting land-use compositions and management contexts among the analyzed farms.

Figure 2 highlights the contribution of the different land cover classes to agroecosystem services, emphasizing the functional role of natural and semi-natural elements within the farm context.

Natural and semi-natural vegetation were the main contributors of regulating services, arable crops contributed most to provisioning services, and semi-natural elements (e.g., ditches, riparian strips) and grasslands supported biodiversity.

Figure 3 shows the total ASCI for each farm along with the specific contribution (ASC_i value) of each LCC (arable crops, grassland, semi-natural vegetation, natural vegetation and structures of the farm) to the overall index. Farm 4 showed the highest total ASCI value (2.01), largely due to the contribution of grassland (1.25). The total ASCI values for farms 1, 2, 3 were 1.77, 1.85 and 1.83, respectively, but with markedly different LCC contributions. For example, farm 2 showed stronger contribution from arable land (1.61) and semi-natural vegetation (0.15). Figure 3 shows that similar total ASCI values may arise from different combinations of land cover classes, underlining the configurational nature of agroecosystem service provision in the analyzed farms.

Focusing on biodiversity services, Table 2 reports average Shannon index values by land cover class, supporting a comparative interpretation of plant diversity across managed and semi-natural elements. The average Shannon index value, calculated across land cover class (LCC) macro-categories, provides a comparative overview of biodiversity across LCCs with different levels of management intensity.

Semi-natural vegetation and grassland were the most species-rich land cover classes and, consequently, showed the highest plant diversity values. Among LCC, ditches provided the highest vegetation biodiversity (Shannon index). These results refer exclusively to vascular plant diversity and represent a snapshot based on a single sampling campaign.

In total, 44 plant families were identified. The most representative were Poaceae (18%) and Asteraceae (11%) while a large proportion of the families fell into the “Other” category each contributing a limited percentage (33% overall). Figure 4 summarizes the relative abundance of plant families across the surveyed farms, providing compositional context to the biodiversity indicators reported above.

Analyzing family distribution across land cover classes (Appendix B) distinct patterns emerge: ditches hosted 28 families showing a prevalence of Asteraceae (14.5%); riparian and uncultivated strips contained 38 different families dominated by Poaceae (17%) with a range of 16.5%; grasslands supported 15 different families with a strong prevalence of Poaceae (32%), with a range of 32.1%; planted forest had 16 families and a prevalence of Fabaceae (13.6%), with a range of 9.1%; natural forests hosted 16 families with prevalence of Asteraceae, Betulaceae, Rosaceae (each contributing 10.5%), with a range of 5.3%. These results highlight differences in plant taxonomic composition across land cover classes.

TABLE 2 Average Shannon index across land cover classes.

Land cover class	Shannon index
Arable Crops	0.21
Natural vegetation	0.79
Forest	0.79
Grassland	0.82
Semi-natural vegetation	0.83
Riparian and uncultivated strips	0.83
Planted forest	0.74
Ditches	0.92

Bold values highlights the main Land Cover Class categories.

3.2 Social and economic indices of sustainability

Social and economic sustainability, evaluated through the adapted PGTool, varied considerably across the four case-study

FIGURE 4
Distribution of plant families identified in the surveyed farms.

farms. Figure 5 provides a comparative visual representation of social and economic indicators, allowing qualitative identification of strengths and weaknesses across farms. Food/feed security was maximized in farm 4, the organic farm, due to the contribution of self-produced forage. Economic performance had the highest score in farm 1 and 3, the farms linked to greater dairy efficiency and resilience and in farm 4, for the plus value of the milk from organic management. Social capital, that considered job offer and employment, and landscape and cultural heritage were maximized in farm 1. Water management scores were generally low except for farm 2, which exhibited higher values associated with groundwater resources and the presence of an efficient irrigation system.

3.3 Environmental impact

Annual environmental impact values are shown in Table 3. Impacts were calculated both per kg of FPCM and per unit of UAA (m^2), reflecting two complementary perspectives on environmental

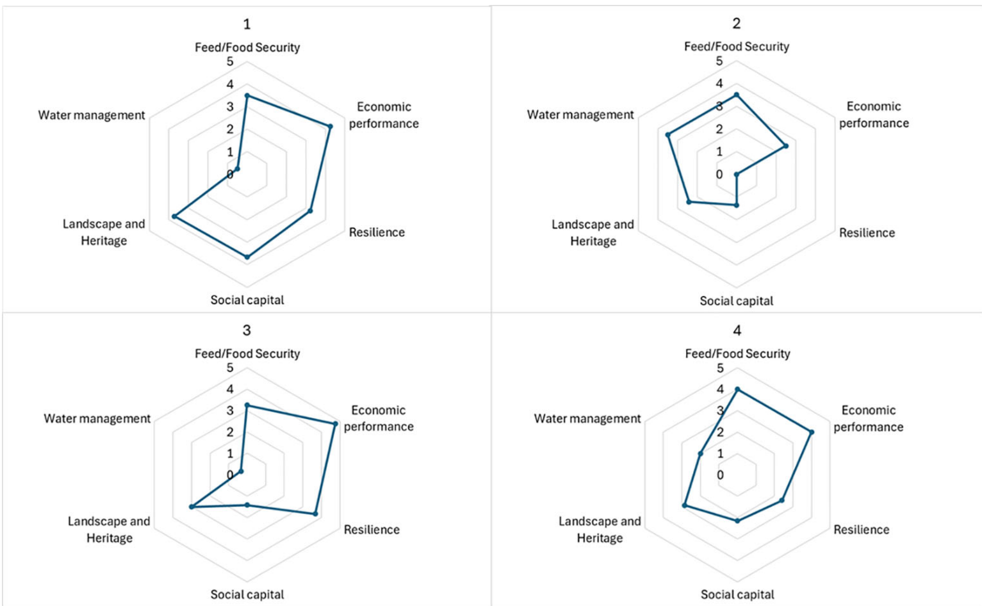

FIGURE 5
Radar charts of social and economic indicators across farms.

TABLE 3 Environmental impact values of milk production expressed per kg FPCM and per m^2 of UAA.

Impact category	Unit	1 kg FPCM Farm 1	Farm 2	Farm 3	Farm 4	1 m^2 UAA Farm 1	Farm 2	Farm 3	Farm 4
Acidification	*mol H+ eq*	0.02	0.03	0.04	0.03	0.10	0.07	0.03	0.08
Climate change	*kg CO2 eq*	1.37	1.61	1.87	1.76	6.11	3.81	1.18	4.23
Climate change - Biogenic	*kg CO2 eq*	0.69	0.83	1.38	0.79	3.10	1.97	0.86	1.90
Climate change - Fossil	*kg CO2 eq*	0.42	0.64	0.50	0.68	1.89	1.52	0.31	1.64
Climate change - Land use and LU change	*kg CO2 eq*	0.25	0.13	0.00	0.29	1.12	0.32	0.00	0.69
Eutrophication, terrestrial	*mol N eq*	0.10	0.13	0.19	0.14	0.45	0.30	0.12	0.34
Resource use, fossils	*MJ*	3.28	5.70	4.86	5.92	14.7	13.5	3.05	14.2
Water use	*m^3 deprivation*	11.1	22.5	18.4	22.2	49.5	53.4	11.6	53.3

performance related respectively to production efficiency and land occupation.

For the climate change impact category, farm 1, which showed the lowest impact value per kg of milk (1.37 kg CO_2 eq/kg FPCM), had the highest impact value per area (6.11 kg CO_2 eq/m^2). Conversely, farm 3 showed the highest values per kg milk (1.87 kg CO_2 eq/kg FPCM) and the lowest per area (1.18 kg CO_2 eq/m^2). Farm 4 had the highest fossil-related Climate Change and Resource use per kg FPCM, while farm 3 had no impact in terms of Climate Change for land use mainly due to the use of organic soybean meal and concentrate feed produced in Italy.

Considering the impact categories expressed for unit of area, Farm 1 had the highest values while Farm 3 the lowest. These differences were associated with contrasting land-use patterns, as Farm 1 and Farm 3 were the farms with the lowest and the highest share of arable land compared to the others. For the water use categories, farms 2 and 4 showed very similar results. Table 3 summarizes the environmental impact results across categories and functional units, highlighting how farm performance varies depending on whether impacts are expressed per unit of product or per unit of land.

Figure 6 shows, for each farm, the Climate change impact expressed as kg of CO_2 eq per kg FPCM (upper panel) and perm^2 of UAA (lower panel), disaggregated by contributing processes.

When the impacts were expressed on unit milk, the largest contribution to the impact was attributable to housing with values ranging from 27.1% on farm 2 to 49.7% on farm4. Manure storage also contributed substantially to the total impact ranging from 21.3% on farm2 to 27.7% on farm 4. Crop production and processing contributed between9.2% in farm 1 and 17.4% in farm2. Evaluating the impacts per unit of UAA, crop-related processes remained important contributors. Farm 4 had the lowest value (4.82%), probably due to the higher share of grassland and the reduced presence of arable crops. Figure 6 highlights how the relative importance of processes shifts depending on the chosen functional unit.

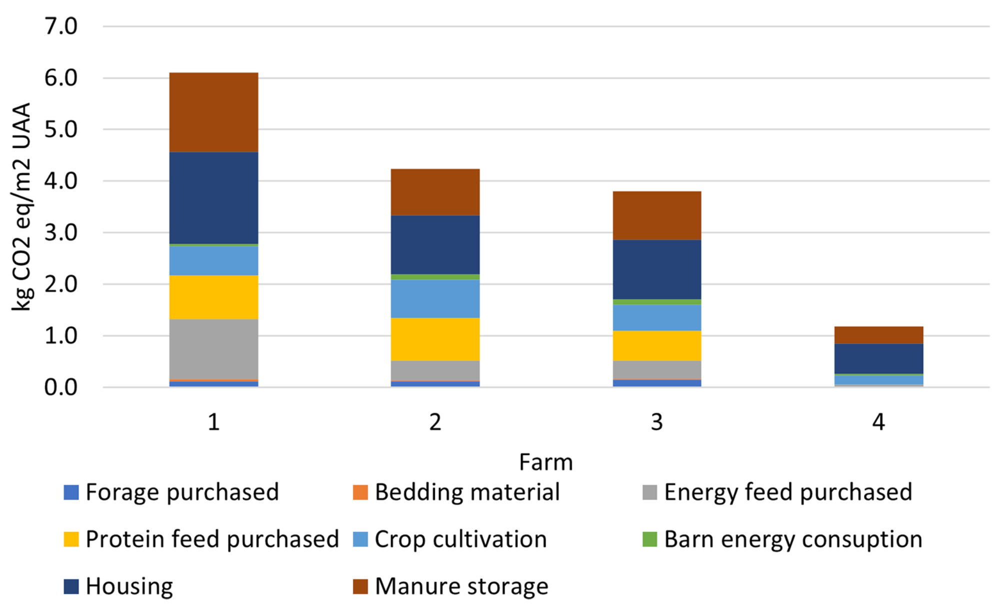

FIGURE 6
Contributions of processes to climate change impact expressed as kg of CO_2 eq/kg of FPCM milk (upper panel) and kg of CO_2 eq/m^2 (lower panel) of UAA.

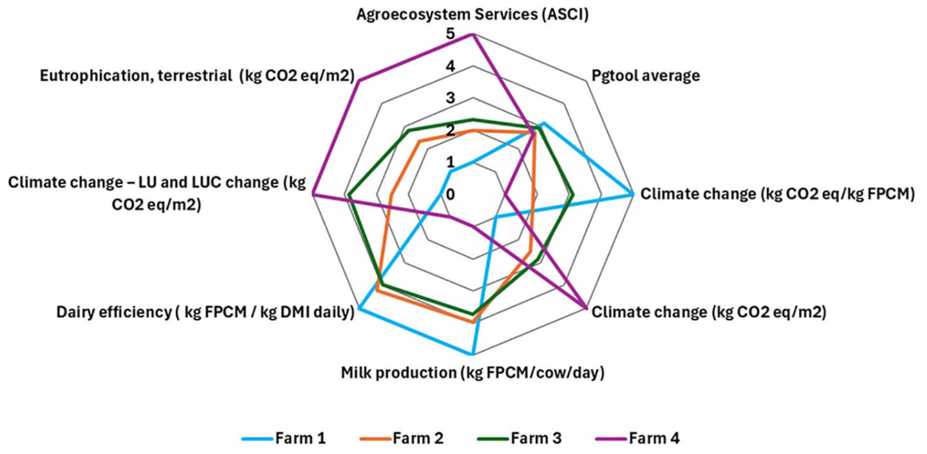

FIGURE 7
Radar chart summarizing the different dimensions of sustainability performance across farms.

3.4 Integrated sustainability assessments

To explore the ability of the framework to capture potential trade-offs among sustainability dimensions, a composite scoring system (1–5) was applied across environmental, social, and economic variables (Figure 7). All the variables were scored on a scale from 1 to 5, where value 1 is the "least favorable" and value 5 "most favorable" in relation to sustainability. Scores were used exclusively for comparative purposes.

Farm 4 showed higher value for ASCI index and for impact categories expressed as unit of area compared to the others reflecting its grassland share and biodiversity while farm 1 had the highest values for indicators related to milk productivity and Climate change expressed per unit of milk. Figure 7 provides an integrated visual summary of the multidimensional sustainability profiles of the analyzed farms, supporting a qualitative and exploratory identification of potential synergies and trade-offs among sustainability dimensions.

4 Discussion

Analyzing the agroecosystem service categories, the farms with the highest values of biodiversity and regulating services were those with the largest share of grassland and semi-natural vegetation. This pattern is consistent with previous studies showing that vegetation disturbance can influence regulating services (Vanacker et al., 2014). Conversely, farms with the highest value of provisioning services had the largest arable crop land, as in this service category crops that provide forages have an important role (Montoya et al., 2019). When services are weighted by land area the ASCI index of the four farms were very similar, even if the contribution of each land cover class varies considerably among the farms. In all cases, arable crops and grassland appeared to be the main drivers of agroecosystem services largely reflecting their dominant share of farm land use. Diversifying agricultural systems, by using both arable crops and grassland, may offer opportunities to enhance ecological synergies, particularly when crop and livestock management are integrated (Franzluebbers and Martin, 2022). Additionally, semi-natural vegetation showed a key importance to the provision of services, in particular supporting biodiversity. Among these areas, grasslands and riparian or uncultivated strips showed the highest contributions and their conservation can have positive effects on plant diversity (Martin et al, 2021), highlighting the potential positive effects of human activities on biodiversity and ecosystem services, depending on the degree and type of anthropogenic pressure.

Regarding biodiversity, Bragaglio et al. (2018) claim that grass-based beef production systems not only support livestock, but they also may provide additional services, especially through the enhancement of biodiversity. The results of the biodiversity assessment highlight an interesting composition of vegetation across land cover classes, in terms of prevalence and diversity of family taxonomy. Ditches and riparian strips hosted the highest number of families with balanced distributions. Forests had the greatest taxonomic homogeneity while grassland hosted fewer families and showed the lowest homogeneity among detected families, with a marked prevalence of Poaceae spp. Grassland hosted a taxonomic family unique to this land cover class (Scrophulariaceae). Notably, among the most represented families some included rare or threatened European plants adapted to arable habitats (Caryophyllaceae, Asteraceae and Brassicacae) (Storkey et al, 2012). Ditches, riparian and uncultivated strips, as well as natural forests, had the highest percentage of Asteraceae; grassland and planted forest had major percentage of Caryophyllaceae; ditches, riparian and uncultivated strips and grassland hosted Brassicaceae.

Considering the characteristics of the farms and the social and economic sustainability, farms achieving high economic performance adopted different strategies: two conventional farms maximized the performance thanks to a good result in terms of revenues. The organic farm achieved high economic performance not through production efficiency but through higher milk price and feed self-sufficiency, ensuring high food/feed security. These findings indicate that, within the analyzed farms, different strategies are associated with high economic performance. However, resilience indicators, as long-term survival ability, were higher in farms with greater production efficiency. Notably, landscape and heritage were not penalized by economic performance, suggesting a potential coexistence between farm profitability and landscape conservation. Only farm 2 had a good score in water management, due to its extensive use of groundwater also for irrigation and efficiency of irrigation system (drip irrigation) whereas the other farms used mainly grid water without efficient irrigation practices. This result reflects both management choices and local hydrological conditions, as these farms were located in areas with relatively high-water availability for agricultural use.

Employment in farms is a critical issue in European dairy farming due to the declining workforce (Hostiou et al., 2020). Social capital scores, defined in terms of job availability and satisfaction, were generally low across studied farms. However, an observed pattern is that the social capital was the highest in farm with the greatest value of landscape and heritage, It would be interesting to investigate further whether aesthetically and culturally valuable workplaces may positively influence labor attraction.

Regarding environmental performance, the farm with the lowest impacts for unit of product had also the highest impacts per unit area, indicating a potential trade-off between product-based and land-based indicators, as previously reported by Pirlo and Lolli (2019).

Farms with the highest biodiversity scores tended to show lower environmental impacts per unit of area; conversely farms with low biodiversity showed higher impacts per area for the most impact categories. This pattern is consistent with the study of Mondière et al. (2024) who found that farms with lower productivity had lower environmental impacts per ha and showed better results in terms of biodiversity. Farm 4 showed the lowest impacts per unit area, despite not being the largest in size, suggesting that environmental impact may be influenced not only by farm size, but also by crop diversity and yields. In the analyzed farms, higher proportion of grassland were associated with lower impact values per unit area. A similar trend was observed for ASCI that was higher in the farm with the highest percentage of grassland (55%). This result agrees with Von Greyerz et al. (2023) who stated that ruminant farms can contribute to AES in several ways and grasslands, used mainly to provide feed for ruminants, are associated with multiple AESs. Additionally, the same farm recorded zero impact, in terms of climate change for land use and land use change per unit area and had the lowest impact values for acidification, eutrophication, resource and water use. These findings suggest that land use simplification may negatively affect ecosystem structures and functions, often reducing AES provision (Yang et al., 2022).

These results highlight that farms must be evaluated as a whole for their complexity. In fact, the farm that appeared to be the most virtuous in terms of land preservation and resource utilization had a high environmental impacts per kg milk, partly due to low production per cow, below the regional average. Across all farms, the biogenic fraction (mainly associated with enteric methane) of the climate change category was the largest contributor, regardless of environmental impact was expressed per unit of kg milk or unit of area.

The integrated sustainability assessment suggests a potential association between environmental impacts expressed by unit of land and AES, whereas productivity indicators appear to be more closely related to with climate change impact per unit of milk. This indicates that, within the limited sample considered, the results of AES, expressed per unit area cannot be directly compared with those expressed per unit of product (Gerrard et al., 2011). Interestingly, social and economic indicators did not show clear differences associated with farm type whereas larger differences were found for AES.

Previous studies highlighted that in extensive livestock production systems, especially in marginal areas, the outputs of LCA should consider not only marketed products but also non-marketable public goods, such as "ecosystem services", related to the multifunctional role of livestock (Bragaglio et al, 2018). The novelty of this study lies in applying an ecosystem evaluation to high-input systems showing that even in intensive systems it may be relevant to consider both environmental impacts and the services that farms provide to the environment and society. Although the total amount of ecosystem services is often higher in extensive systems, as confirmed by this study, the geographic location of farms and the competition for land with other human activities must also be considered. In fact, areas most suitable for livestock farming frequently are also those under great pressure from land consumption. In Lombardy, for instance, 12.2% of land is already consumed, the first share in Italy (ISPRA, SNPA, 2024), which makes the ecosystem services offered by dairy farms particularly valuable in these areas.

This study presents some limitations that should be considered when interpreting the results. First, the limited number of farms (n = 4) reflects the pilot and exploratory nature of the study and suggests that caution is needed when extending the findings beyond the analyzed cases. Second, although the selected farms were chosen to represent different management conditions, they may not fully encompass the entire variability of dairy farming contexts. Third, the scoring approach used to integrate different sustainability dimensions combines quantitative and qualitative indicators and may include a degree of expert-based evaluation, However, this approach is grounded in literature references and standardized criteria, ensuring consistency and transparency in the assessment. In addition, biodiversity was assessed through a single sampling campaign, which provides a representative snapshot of plant diversity while future studies could further explore seasonal and inter-annual dynamics. Finally, the analysis follows an observational and descriptive approach; therefore, the relationships observed among variables should be interpreted as indicative patterns within the analyzed farms providing a useful basis for future, more comprehensive investigations.

5 Conclusions

This study explored the feasibility of combining multiple dimensions of dairy farm sustainability into a single integrated framework. Despite the limited sample of four farms, the results illustrate the potential of the approach to highlight trade-offs and synergies among sustainability dimensions. Biodiversity and regulating services were associated with land-based impact categories, whereas provisioning services were more frequently related to product-based impacts. Although the final scores for Agroecosystem service Index were very similar across farms, the different vegetation categories contributed differently. Although based on a limited sample, the findings of this pilot study indicate that, within the analyzed farms, proper management of marginal areas (e.g., field edges, ditches, canals, and field borders) and the inclusion of grassland may contribute to biodiversity and regulating services while maintaining production performance.

The development of this framework highlights that a comprehensive assessment of farm sustainability con not rely solely on environmental impacts alone but should also consider the ecosystem services provided by farms to the surrounding environment and communities, including cultural heritage and social benefits.

The main contribution of this work lies in testing and refining a methodological framework for integrated sustainability assessment. Future research should apply this approach to a larger number of farms and across different regions and production systems, including temporal replication, in order to validate the method and strengthen its potential applicability for policy analysis, certification schemes, and decision-making in the livestock sector.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

NP: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. SB: Data curation, Investigation, Methodology, Writing – original draft. AS: Formal analysis, Project administration, Supervision, Writing – review & editing. AT: Formal analysis, Validation, Writing – review & editing. GR: Funding acquisition, Validation, Writing – review & editing. LB: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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