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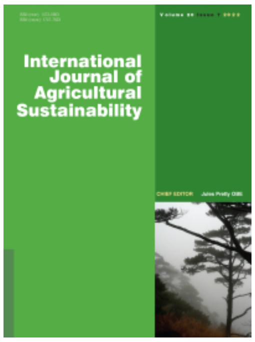


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# Exploring relationships among different sustainability aspects in innovative livestock systems in Europe

Elena Diaz Vicuna[a], Nina Adams[b,c], Laurence Smith[b,d], Magdalena. Durand[b], Coen van Wagenberg[e], Enora Caron[f], Agnes van den Pol-van Dasselaar[g], Lukas Baumgart[h], Soline Schetelat[i], Mignon Sandor[j], Adrian Gliga[j], Sandrine Espagnol[k], Heidi Mai-Lis Andersen[l], Robert Borek[m], Piotr Jurga[n], Noa van Leuffen[g], Jasper L.T. Heerkens[g], Jenny Yngvesson[o], Annabel Oosterwijk[e], Jessica Stokes[p], Claudio Forte[a] and Anna Hessle[o]

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**ABSTRACT**

European livestock farming reflects a range of systems characterized by diverse innovations to increase sustainability. This study aimed to highlight the relationships among different aspects of sustainability in various types of systems. Data were retrieved from 106 farms containing different animal species (dairy cattle, beef cattle, pigs and poultry), using a modified version of the Excel-based questionnaire public goods tool. Each farm was assigned scores for 12 spurs (indicators) of sustainability. Based on these results, the farms were allocated into five clusters. Correlations among the spurs were evaluated, both across all farms and cluster-wise, with contrasting results. When analysed across all farms, several spurs from the environmental dimension were positively correlated with each other. Further, many of the environmental spurs were negatively correlated with spur profitability, which was positively correlated with spur social wellbeing and farm business resilience. A comparison of cluster-wise correlations showed a positive correlation between environmental spurs and spur profitability for large farms but a negative correlation for small farms. The diverging, yet complementary, correlation results from this study open the field to sustainable pathways that are capable of connecting realities with differing production systems and geographical areas while also incorporating their unique features.

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Sustainability assessment; Public Goods tool; environmental sustainability; social sustainability; economic sustainability

## 1. Introduction

The Food and Agriculture Organization of the United Nations (FAO) (2014) defines sustainable development as a dynamic concept that encompasses a variety of principles belonging to three main dimensions: environmental, economic and social. Respecting these three dimensions is key to ensure the sustainability of a product, sector, or supply chain (Braun & Ghosh, 2020; Paraskevopoulou et al., 2020). At the same time, the phenomena characterized in recent decades, such as the exponential growth of the global population, climate change and the diminishing availability of natural resources, have directly contributed to the

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creation of a general climate of food insecurity, particularly affecting food products of animal origin (Foley et al., 2011; García-Díez et al., 2021; Stoddart, 2013). As a result, consumers' preferences for such products have evolved, led by increasing awareness of the environmental challenges linked to their production and growing concern over their contribution to climate change (Spada et al., 2024; Stranieri et al., 2022). In response to this situation, the need to enhance the sustainability of the food supply chain has emerged as an environmental, social and economic priority, affecting the scientific community, producers and consumers alike (Kiran et al., 2023; Leip et al., 2015; Lovarelli et al., 2020). These findings underline the need for industry and institutions to align with both supply-side improvements and demand-side expectations. In the European Union (EU), the legislative response to these events has been represented by the Farm2Fork Strategy along with the various reforms of the Common Agricultural Policy (CAP), which focuses on the promotion of a more sustainable livestock sector (Kiran et al., 2023).

There is a general recognition that animal farming systems continually play a pivotal role in societies owing to their numerous and diverse functions, which are attributable to both monogastrics and ruminants. These range from transforming materials that are inedible to humans, such as grass and side streams (forage, crop residues and agricultural by-products that are generally unsuitable for human consumption), into nutrient-rich food to promote the vitality of rural territories, especially through the provision of economic inputs (Gerrard et al., 2012; Leroy et al., 2022; Upton, 2004). Workers within the agricultural sector account for approximately 4% of the total EU employment (Eurostat, 2022) and then there are also suppliers, service and industry based on primary production. Of the total output from agricultural activities in the EU, 40% is derived from animal production (Peyraud & MacLeod, 2020), and more than 60% of the total utilized agricultural area, including arable land and pastureland, is used as a food source for animals (Guyomard et al., 2021). Additionally, specific environmental and cultural benefits are linked to certain livestock production systems (Dumont et al., 2019), such as forage and pasture-based rearing, particularly when grazing unfertilised, semi-natural grasslands (Eriksson, 2022; European Environment Agency, 2020). The grazing process influences flora and fauna through a combination of mechanisms, including biting and trampling, removal of biomass and redistribution of nutrients. Grazing also affects temperature and light levels in the vegetation cover and at the soil surface. Together, these mechanisms lead to grazing-tolerant, low-growing and short-lived species of vascular plants becoming more common compared to unmanaged or fertilized land (Pykälä, 2005). These systems also enhance water and soil quality and maintain local cultural values and, ultimately, the landscape's own identity (Bele et al., 2018; Guyomard et al., 2021).

However, it is imperative to address livestock's less favourable impacts, especially from the most intensive systems. The sector contributes to the pollution and exploitation of natural resources, often at the expense of humans (e.g. via feed and food competition) (Muscat et al., 2020). Indeed, EU animal farming is responsible for up to 80% of the agricultural sector's environmental footprint through its negative effects on water and air quality, biodiversity and soil acidification (Lai & Kumar, 2020; Leip et al., 2015; Lovarelli et al., 2019; Post et al., 2020; Reidsma et al., 2006; Yan et al., 2024; Zucali et al., 2020). To mitigate the environmental downsides of animal-derived food supply chains, various strategies have been proposed. Although approaches differ depending on species and production systems, major efforts are focused on improving productive and reproductive efficiency, parallel to a more efficient use of available resources (Caccialanza et al., 2023; Leinonen & Kyriazakis, 2016; Shurson & Kerr, 2023; Veltman et al., 2021).

Furthermore, in recent years, the European livestock sector has undergone a process of re-evaluation, shifting from being viewed primarily as a major contributor to environmental degradation to being recognized as a potential driver of a sustainable circular bioeconomy. This change in perspective has been reinforced by the emergence of numerous innovative farms offering viable approaches for a more sustainable and competitive future (Reg. EU 2021/2115). In parallel to this, attention is growing towards the variety of public goods that these systems produce in addition to food, such as contributing to the vitality of rural territories, enriching the agricultural landscape and promoting biodiversity (Nigmann et al., 2018).

Understanding the range of benefits and drawbacks related to these systems and their innovations from a sustainability perspective is crucial for the development of further policies and practices which are suitable for the diverse European landscape.

At present, studies assessing on-farm sustainability are typically focused on a specific animal species or perform the evaluation from a single perspective only, most often the environmental one, with less attention to economic and social aspects (Arvidsson et al., 2020; Arvidsson et al., 2021; Di Vita et al., 2024; Gunnarsson et al., 2020a, 2020b; Kheiralipour et al., 2024; Pahmeyer & Britz, 2022; Zira et al., 2021). Moving beyond isolated assessments and toward a more integrated understanding that is capable of considering multiple farms differing in terms of geographical location, animal category and production systems would facilitate the identification of interconnections among different dimensions of sustainability while also enabling meaningful comparisons across varied farm types. The employment of a multi-level framework that integrates environmental, economic and social perspectives is therefore essential (Galdeano-Gómez et al., 2017; Sulewski et al., 2018). In recent years, various sustainability assessment tools have been developed, aimed at measuring and monitoring sustainability using an integrated approach (Binder et al., 2010; Coteur et al., 2020). One of these evaluation protocols is the Public Goods (PG) tool (Marta-Costa & Silva, 2013).

In the present study, the PG tool assessment was applied for the first time to a range of innovative livestock farming systems in Europe to provide an analysis of the underlying relations among different sustainability aspects and to answer the following research question: 'How do the environmental, economic and social pillars of sustainability interact across innovative European livestock farming systems, and are these patterns consistent across them?'.

## 2. Materials and methods

### *2.1 Public goods (PG) tool*

The PG tool is a Microsoft Excel-based form that was initially developed by Gerrard et al. (2012) to analyze the contribution of public goods from organic dairy farms in England. It is characterized by a vast coverage of sustainability criteria and a highly versatile protocol that is easily adaptable to best suit a specific study design (Marchand et al., 2014). These technical reasons, together with the presence of team members with extensive expertise in the tool, guided its selection and facilitated its adaptation to the needs of the present study.

The adaptation of the original protocol was driven by three necessities. First, it was necessary to shift the aim of the data collection to a more sustainability-focused study rather than the delivery of public goods. Each farm's sustainability evaluation had to be conducted through the analysis of its environmental, economic and social dimensions, in accordance with the FAO (2014) definition of a 'sustainable food value chain'. Second, the version used in this study required a collection of comparable data from a broader and more diverse sample in terms of animal species and country-specific characteristics aside from just organic dairy farms. Third, the use of literature from the last decade underpinning the assessment should be enabled. Adaptation of the tool and education on its functions were conducted in an interactive process with the persons who were to be responsible for the data collection. Experts in different areas were contacted with direct questions. Most modifications concerned economic data, social issues and agri-environmental management, and these are reported in Table S1 (Supplementary material).

Prior to the sustainability analysis, production and structural data (farm dimensions, presence and dimensions of crops, and stocking rates) were collected. Importantly, the stocking rate was considered at the farm level (LU/ha), hence referring to the total number of animals, expressed in livestock units (LU), per hectare of utilized agricultural area (UAA) of the entire farm.

An evaluation of environmental, economic and social sustainability was performed using a total of 12 spurs (indicators):

- Environmental sustainability: agri-environmental management, landscape and heritage, soil management, water management, manure and fertilizer, the NPK budget and energy and carbon.
- Economic sustainability: Profitability, farm business resilience, system security and diversity.
- Social sustainability: Animal welfare and social well-being.

Each spur contained three to six activities (for a total of 52), which, in turn, were composed of three to six questions. Each question was assigned a score ranging from 1 (poor sustainability) to 5 (excellent sustainability) based on the answers provided by the respondent. There were questions with quantitative answers retrieved from farm recordings and questions with semi-quantitative and qualitative answers designed as multiple-choice questions with a list of options. For questions identified as ambiguous, an explanatory box was added. Additionally, to ensure comparability across the data collected from such diverse farm types (dairy, beef, pork and poultry), the PG tool was adapted to account for species-specific management practices. This included the incorporation of a 'not applicable' (n/a) option for questions not relevant to certain livestock types (e.g. milking routines for monogastrics), thereby avoiding artificial score inflation or deflation. The core structure of the tool remained consistent across farms, enabling a common sustainability assessment framework while accommodating key structural differences. These adaptations can be found in the PG tool file uploaded in the data repository (https://doi.org/10.5281/zenodo.17709094) and were implemented in collaboration with field experts during the tool refinement phase. The arithmetical mean of the scores for the questions within an activity composed the score for that activity, rounded off to the nearest integer. Thus, an activity consisting of several questions was not weighted more heavily than one requiring only one question. In turn, the arithmetic mean of the scores for the activities within a spur composed the summarised score for that specific spur.

All the evaluated parameters (questions, activities and spurs) were organised in an Excel file workbook, used to conduct the interviews, and structured with a sheet per spur each with its related questions and activities. The scoring methodologies for each spur and references for the scoring are reported in Table S1 (Supplementary material), and a description of the spurs' reliance on quantitative data is reported in Table S2 (Supplementary material).

## 2.2 Farms and data collection

The data collection process involved interviews with farmers belonging to a total of 106 farms and was divided into 13 groups, each organized around a theme of innovation in practice and located in nine different European countries. Each group was identified as a practice Hub (PH).

The PHs were selected to cover the four types of innovation defined by the Organisation for Economic Cooperation and Development (OECD): product, processing, marketing and organization (Gault, 2018), which were applied in the context of animal farming. The study sample was therefore characterized by a broad range of existing innovations on production, marketing and organisation levels, intensive to extensive systems and mainstream to niche products. Furthermore, the PHs contained different animal species, including farm operations with dairy cattle, beef cattle, pigs and poultry for meat and eggs (Table 1; List S3, Supplementary material). The number of farms per PH varied owing to the availability of farms and heterogeneity within each PH.

To apply the PG tool evaluation, an interview was carried out with one or two representatives of each farm (i.e. owners, farm managers). The interviews were conducted by one or two trained researchers. Each interview

**Table 1.** Description of practice hubs (PHs) with innovative European livestock farms where sustainability data was collected, country of residence, breed of main livestock species, description of innovation and number of farms surveyed. PH 7 did not complete the data collection and was therefore not included.

| PH NO. | Country | Species | Innovation | Farms |
|---|---|---|---|---|
| 1 | Germany | Dairy | 100% pasture-fed cow-calf dairy systems | 10 |
| 2 | France | Dairy | Management for maximisation of C sequestration in pasture | 5 |
| 3 | Romania | Dairy | Dairy with agroforestry aiming for self-sufficiency in protein-based feed | 10 |
| 4 | Sweden | Dairy | More-from-less dairy systems utilising on-farm advice and carbon footprinting tool | 7 |
| 5 | France | Pig | Conventional production utilising manure for biogas | 5 |
| 6 | Denmark | Pig | Organic farmers utilising 'green-protein' from grass/clover working with feed company and refinery | 3 |
| 8 | Netherlands | Pig | Conventional pig production with innovative flooring (solid floor with a layer of material for rooting for all ages) and a focus on biodiversity | 4 |
| 9 | United Kingdom | Beef | 100% pasture-fed beef systems utilising mob grazing, herbal leys and mobile slaughterhouses and Community Supported Agriculture | 19 |
| 10 | Italy | Beef | New breeding methodology for 'mountain pasture' with own certification/label development | 6 |
| 11 | Sweden | Beef | Quality assured (IP SIGILL) production system for beef and sheep on HNV semi-natural pastures together with label development | 10 |
| 12 | Poland | Poultry | Agri-tech innovation for improved welfare | 11 |
| 13 | France | Poultry | Farmer co-operative producing and sharing of compost from plant-based litter | 13 |
| 14 | Netherlands | Poultry | Closed-loop egg production feeding food processing waste and recycling manure | 3 |

lasted four to eight hours and was conducted either in person or remotely from December 2022 to May 2023. All the subjects involved provided written informed consent and were assured of confidentiality and anonymity.

### 2.3 Statistical analysis

All the analyses were performed using R statistical software (v4.3.0; R Core Team 2023).

To classify the diverse range of farms into homogeneous groups based on the spurs' results, a heatmap cluster analysis of the farms was performed on scaled data using the 'ComplexHeatmap' package (Gu et al., 2016; Gu, 2022), which applies hierarchical clustering by default, using complete linkage and Euclidean distance. This method was preferred over alternative approaches, such as k-means, as it does not require pre-specifying the number of clusters and can better accommodate unbalanced group sizes, which aligns with the heterogeneous nature of the dataset (e.g. different species, innovation types and geographical contexts) (Wani, 2024). Given the exploratory aim of classifying farms based on a novel scoring system (the 'spurs'), hierarchical clustering allows for the assessment and visualization of the nested similarity structure among farms without imposing assumptions on cluster shape or count while also providing an intuitive representation of relationships via the heatmap. Subsequently, Kruskal–Wallis analysis and post hoc analysis, including Benjamini–Hochberg's correction, were performed using the 'agricolae' package (de Mendiburu, 2023) to determine whether differences in spur scores between the identified clusters were statistically significant. The results were plotted using the 'ggplot2' package (Wickham et al., 2016).

Within each cluster and across all farms together, a Spearman correlation analysis using the rcorr function from the 'Hmisc' package (Harrell & Dupont, 2024) was performed to measure both the strength and direction of association between the spurs, following confirmation that all the variable pairs met the monotonicity assumption. Correlations found to be statistically significant ($p$-value < 0.05) were further investigated by identifying the questions leading the correlation based on the relative weight of each question in the spur. Additionally, the interquartile range (IQR) and median of the scores of each question were calculated.

## 3. Results

### 3.1 Descriptive data

Figure 1 illustrates the average, median and range of values for each spur across all farms. Considering the average, Profitability was reported with the lowest scores, whereas Soil management presented the highest scores.

The heatmap analysis allowed for the identification of five distinct clusters (Figure 2), described in both Tables 2 and S4 (Supplementary material).

Cluster 1 was a mixed cluster with both monogastric and ruminant farms, with a majority of monogastric (69%), medium-sized farms, and a medium stocking rate expressed as livestock units per farm hectare (LU/ha). This cluster represented all four animal types and seven countries and displayed the highest Profitability score among all the clusters. Conversely, the majority of the environmental spurs reported lower-than-average scores, with the exception of Manure management, which, together with Animal welfare, Social wellbeing and Farm business resilience, presented higher-than-average scores.

Cluster 2 was an exclusively monogastric cluster characterized by a small farm size and very high stocking rate, with the French broiler farms from PH13 comprising 57% of the cluster. It reached the lowest scores in seven spurs (Agri-environmental management, Landscape and heritage, Water management, NPK budget, Energy and carbon, Animal welfare and System security and diversity) but higher-than-average scores for Profitability and Soil management.

Cluster 3 was a solely ruminant cluster, predominantly consisting of dairy farms, characterized by a small farm size and very low stocking rate. The cluster was dominated by the Romanian dairy farms from PH3, which represented 60% of the farms in the cluster. The lowest scores were reached for six spurs (Soil, Water and Manure management, Social wellbeing, Profitability, and Farm business resilience) but presented higher than average performances for Agri-environmental management, Landscape and heritage, NPK budget and Energy and carbon.


**Figure 1.** Average, median and range (min & max) for each of the 12 sustainability spurs analysed with the Public Goods tool (1 is poor sustainability, 5 is excellent sustainability) for 106 European innovative livestock farms.

Cluster 4 was a ruminant-dominated cluster, with a minor share of poultry farms. It was characterized by an average large farm size and low stocking rate and was represented by farms from seven countries. This cluster reached higher scores than the other clusters for eight spurs, Agri-environmental management, Landscape and heritage, Water management, Manure and fertilizer, NPK budget, Animal welfare, Social wellbeing, and Farm business resilience and a higher-than-average score for all spurs.

Finally, cluster 5 was a ruminant-dominated cluster with a minor share of poultry farms, characterized by a medium farm size and a low stocking rate. British (PH10) and Swedish (PH11) beef farms and German dairy farms (PH1) comprised the largest share. The highest scores were reached for three spurs (Soil management, Energy and carbon and System security and diversity), and higher-than-average scores were obtained for Agri-environmental management, Landscape and heritage, Water management, Manure and fertilizer, NPK budget, Animal welfare and Social wellbeing. Lower-than-average scores were observed for the two remaining spurs, Profitability and Farm business resilience.

The analysis showed significant differences in sustainability performance between the clusters (Supplementary material, Table S5). For example, clusters 1 and 2 had lower scores for the spurs Agri-environmental management, Landscape and heritage and NPK budget compared to clusters 3, 4 and 5; however, cluster 1 presented a higher score for Manure and Fertilizer, and cluster 2 for Soil management.

## *3.2 Correlations*

Across all investigated farms, there were 33 significant correlations among the different spurs, out of 66 theoretically possible ones (Table 3, column all; supplementary material, Table S6). Spurs related to environmental sustainability presented seven correlations with spurs of Social sustainability, six of which

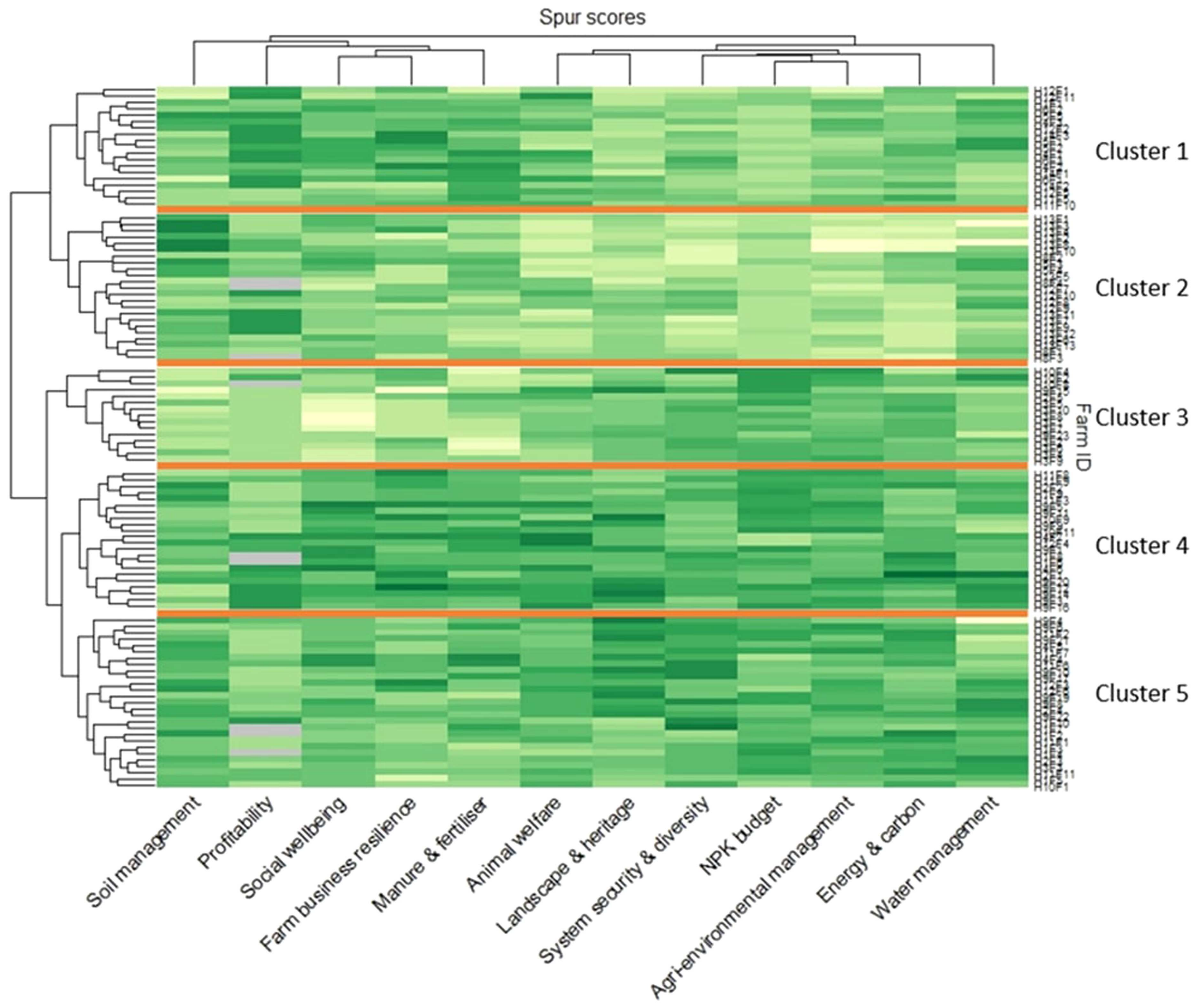


**Figure 2.** Heatmap of standardised values (spur mean is 0, variance is 1) of the different spur scores; each column identifies a single spur, each row identifies a single farm, and each cell represents a specific farm's spur score. The colour intensity of the cells across a column reflects the distance from the mean of the spur, where the light colour is a short distance and the dark colour is a long distance. Grey identifies n/a.

**Table 2.** Characteristics of the five clusters composed of European innovative livestock farms, where allocation was based on the sustainability scores of the farms. Farm size indicates the utilised agricultural area, ha is hectare and a livestock unit (LU) is standardised according to Eurostat (2024).

| | Livestock type (% and number of farms) | | | | | | | | Farm size (ha) | | Stocking rate (LU/ha) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster | Dairy (%) | Dairy (*n*) | Beef (%) | Beef (*n*) | Pork (%) | Pork (*n*) | Poultry (%) | Poultry (*n*) | Mean | Median | Mean | Median |
| 1 | 21 | 4 | 11 | 2 | 32 | 6 | 37 | 7 | 147.5 | 85.0 | 9.2 | 1.3 |
| 2 | – | – | – | – | 26 | 6 | 74 | 17 | 36.3 | 20.0 | 78.3 | 15.6 |
| 3 | 67 | 10 | 33 | 5 | – | – | – | – | 49.0 | 24.2 | 0.5 | 0.5 |
| 4 | 32 | 7 | 64 | 14 | – | – | 5 | 1 | 552.4 | 141.3 | 0.8 | 0.5 |
| 5 | 41 | 11 | 52 | 14 | – | – | 7 | 2 | 152.8 | 107.0 | 0.8 | 0.5 |

were positive correlations. Spurs related to environmental sustainability also presented eleven correlations with spurs of economic sustainability, of which six were positive correlations. Economic spurs presented three positive correlations with the social ones.

Out of the 33 spur–spur correlations reported across all farms, a total of 31 were also observed in at least one of the five clusters (Table 3; Supplementary material, Tables S6–S11). In 21 of these cases, the clusters' correlations were inconsistent with the same correlations across all farms, being positive within clusters while negative across all farms or vice versa. Nine of them also showed inconsistency across clusters. Inconsistency across clusters was also present in a further five correlations that lacked a corresponding

**Table 3.** Graphical representation of correlations between 12 sustainability spurs of environmental, economic and social dimensions, based on PG tool data across all the 106 European livestock farms studied (All) and cluster wise (1–5). For significant correlations only, Spearman's correlation coefficient value is reported; strength of correlation is illustrated by *(*p*-value ranging between 0.05 and 0.01), **(*p*-value ranging between 0.01 and 0.001) and ***(*p*-values lower than 0.001). Details can be found in Supplementary materials, Tables S6–11.

| Spur 1 | Spur 2 | All | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| Agri-environmental management | Landscape & heritage | 0.53** | | | | | −0.15** |
| | Soil management | −0.09** | | −0.46** | | | |
| | Water management | | | 0.49** | 0.63*** | | |
| | Manure & fertiliser | | | | −0.46** | | 0.02* |
| | NPK budget | 0.75** | | | 0.17* | | |
| | Energy & carbon | 0.55** | | | −0.37* | | |
| Landscape & heritage | Soil management | −0.03* | | −0.44** | | −0.22* | 0.22* |
| | Water management | | | | −0.45* | | |
| | Manure & fertiliser | | 0.37*** | −0.33** | | | |
| | NPK budget | 0.50*** | | −0.25* | | | −0.04** |
| | Energy & carbon | 0.38** | | | | | −0.24** |
| Soil management | Water management | | 0.47* | | | | |
| | Manure & fertiliser | | | | | −0.10* | |
| | NPK budget | −0.23** | | | −0.31** | | −0.45*** |
| | Energy & carbon | −0.09** | | | 0.22** | | −0.17* |
| Water management | Manure & fertiliser | | −0.49* | | −0.27* | | −0.41* |
| | NPK budget | | | | 0.36** | | |
| | Energy & carbon | | | 0.56*** | | | |
| Manure & fertiliser | NPK budget | | | | | | |
| | Energy & carbon | | | 0.68* | 0.57** | | |
| NPK budget | Energy & carbon | 0.47*** | | | −0.58** | −0.45** | 0.45** |
| Animal welfare | Social wellbeing | | | | | 0.41* | |
| System security & diversity | Profitability | −0.23*** | | | | | |
| | Farm business resilience | | | | | | |
| Profitability | Farm business resilience | 0.29** | | | 0.58*** | | |
| Animal welfare | Agri-environmental management | 0.46* | | | −0.47*** | −0.28** | |
| | Landscape & heritage | 0.53*** | | 0.50* | | 0.14* | |
| | Soil management | −0.17* | | −0.83*** | | −0.25* | 0.24* |
| | Water management | | −0.56*** | | −0.40** | | |
| | Manure & fertiliser | | 0.34* | | | | |
| | NPK budget | 0.37* | | | | | −0.40* |
| | Energy & carbon | 0.36* | | | | | −0.34** |
| Social wellbeing | Agri-environmental management | | | | 0.56** | | |
| | Landscape & heritage | | | | | 0.17* | |
| | Soil management | 0.25* | | | −0.38* | −0.47** | |
| | Water management | | | | | | |
| | Manure & fertiliser | 0.57* | | | −0.53*** | 0.60*** | |
| | NPK budget | | | | 0.39** | | |
| | Energy & carbon | | | 0.43* | −0.67** | | |
| System security & diversity | Agri-environmental management | 0.52*** | | | | | −0.31* |
| | Landscape & heritage | 0.56*** | | 0.54** | | | |
| | Soil management | −0.13** | | −0.40** | | | |
| | Water management | | | | | | −0.39** |
| | Manure & fertiliser | | | | −0.09* | | 0.54** |
| | NPK budget | 0.55*** | | | | | |
| | Energy & carbon | 0.47*** | | | −0.43* | | |
| Profitability | Agri-environmental management | −0.22** | −0.31* | | 0.58** | | |
| | Landscape &heritage | −0.21** | −0.20* | | −0.43* | 0.31* | |
| | Soil management | <0.01* | | | | −0.50* | |
| | Water management | | 0.06* | | 0.59*** | 0.54* | |
| | Manure & fertiliser | | −0.24* | | | | |
| | NPK budget | −0.29*** | −0.22* | | 0.58*** | −0.41* | |
| | Energy & carbon | −0.11** | | | −0.40* | | |
| Farm business resilience | Agri-environmental management | | | | 0.89*** | | |
| | Landscape & heritage | | | | | | 0.29** |
| | Soil management | | | | | | 0.35*** |
| | Water management | | 0.31* | | 0.76*** | | |
| | Manure & fertiliser | 0.42* | | | −0.52** | | 0.24* |
| | NPK budget | | | −0.08* | 0.21* | | −0.37*** |
| | Energy & carbon | | | | −0.42* | | −0.18** |
| System security & diversity | Animal welfare | 0.42 ** | | 0.52*** | | | |
| | Social wellbeing | | | | 0.36* | | |
| Profitability | Animal welfare | | <0.01** | | −0.32* | 0.55** | |
| | Social wellbeing | 0.18** | | −0.53*** | 0.50* | | |
| Farm business resilience | Animal welfare | | | | −0.41** | | |
| | Social wellbeing | 0.56* | 0.47** | | 0.46** | | |

correlation across all farms (Table 3; Supplementary material, Tables S6–S11). These contradictory results between correlations across farms and within clusters were observed in 60%–62% of the correlations involving environmental and social spurs and in 44% of the correlations involving economic spurs. Among the correlations across all farms, 64% of the positive correlations and 45% of the negative correlations showed inconsistencies when analysed within clusters. Moreover, 30 spur–spur correlations were identified within one or more clusters that were not detected in the overall farm analysis. These correlations were evenly distributed among environmental, economic and social spurs.

Cluster 1 presented 13 correlations (Table 3; Supplementary material, Table S7). The profitability spur presented the highest number of correlations (six), of which a positive correlation was shown with Water management and Animal welfare. Negative correlations were reported with Agri-environmental management, Landscape and heritage, Manure and fertilizer and NPK budget.

Cluster 2 was characterized by 15 correlations (Table 3; Supplementary material, Table S8). Among these, Landscape and heritage spur presented the greatest number of correlations (five). There were two positive correlations with Animal welfare and System security and diversity and three negative correlations with Soil management, Manure and fertilizer, and NPK budget.

Cluster 3 presented a total of 36 correlations (Table 3; Supplementary material, Table S9), the majority of which involved Social wellbeing and Farm business resilience (eight correlations each). The former presented positive correlations with all the economic spurs, hence Profitability, Farm business resilience and System security and diversity. Additionally, it presented positive correlations with Agri-environmental management and NPK budget, whereas negative correlations were presented with Soil management, Manure and fertilizer, and Energy and carbon. Farm business resilience presented positive correlations with Profitability, Agri-environmental management, Water management, NPK budget and Social wellbeing, whereas negative correlations were presented with Manure and fertilizer, Energy, and carbon and Animal welfare.

Cluster 4 had 15 correlations (Table 3; Supplementary material, Table S10), of which Soil management and Profitability spurs presented the highest number (five correlations each). The former was negatively correlated with Landscape and heritage, Manure and fertilizer, Animal welfare, Social wellbeing and Profitability. In addition to a negative correlation with Soil management and NPK budget, Profitability correlated positively with the Landscape and heritage, Water management and Animal welfare spurs.

Finally, cluster 5 presented 20 correlations (Table 3; Supplementary material, Table S11), with Landscape and heritage and Farm business resilience spurs displaying the highest number of correlations (five correlations each). The former correlated negatively with Agri-environmental management, whilst the latter correlated positively with Manure management. Both Landscape and heritage and Farm business resilience correlated negatively with the NPK budget and Energy and carbon, positively with Soil management and positively with each other.

## 4. Discussion

### *4.1 Key aspects of the study*

In recent years, European livestock farming has embraced a growing number of innovative systems aimed at enhancing sustainability (Reg. EU 2021/2115). However, the literature exhibits significant gaps regarding an exploration into the complex framework of rules and factors that define the concept of sustainability within the livestock sector (Martin et al., 2020). This highlights the need to develop a comprehensive assessment of the multidimensional elements that define sustainability within individual systems to accurately identify trade-offs and synergies. This study used a multidimensional approach and investigated the relationships among various measurements (spurs) of sustainability on 106 European farms gathered around 13 different innovations aimed at increasing various aspects of sustainability. A comprehensive adaptation of the PG tool was undertaken to best reflect the varying conditions of the study farm operations. The number of farms involved in the study, along with the extensive data collected for each unit, facilitated the development of a large and comprehensive dataset. Additionally, the methodology employed for this study enabled the standardisation of data collection, allowing for comparisons between farms presenting high levels of differentiation in terms of production, marketing and organisation. The inclusion of farms from such diverse livestock sectors (dairy, beef, pork and poultry) raises important considerations regarding the comparability of sustainability outcomes. These systems differ markedly in terms of typical farm size, production intensity, economic margins, labour organisation and technological adoption. Nevertheless, this heterogeneity was a deliberate choice, as it allowed for the identification of sustainability dynamics and correlations that transcend sectoral boundaries, as confirmed by the heatmap clusters' results. The objective was not to compare sectors *per se* but to explore how various sustainability aspects interact with each other across a wide range of real-world farming contexts. However, despite the substantial quantity of data gathered, the complexity of these systems consequently hinders exploration into the causal nature of the identified relationships. Hence, it could be that a high score of a particular spur, e.g. Animal welfare, resulted in a high score of another spur, e.g. Profitability, due to healthier animals (Dawkins, 2016). However, the opposite could also be the case that a high Profitability score provides the opportunity to implement investments improving Animal welfare. A positive relationship between two spurs could also be due to a third factor influencing both spurs. A potential third factor could be the eagerness in embracing innovations, particularly when considering that the studied farms were managed by persons who could most likely be defined as early adopters (Zagata & Sutherland, 2015).

Moreover, the probability of finding correlations among spurs may have been influenced by both the number of underlying activities and types of questions. With few questions and few answers, extreme values could be obtained, and some of the correlations identified were influenced by a specific question contributing to the scoring of more than one spur. One example could be the question related to the provision of public access to animals, which contributed to a high score for System security and diversity for marketing reasons but a low score for Animal welfare due to biosecurity reasons (Table S1). Furthermore, only 23 of the 191 questions were based on concrete information based on quantitative data, such as areas of various land types, type and number of livestock, type and amount of energy, and economic figures from bookkeeping (Supplementary material, Table S2 and raw data file - https://doi.org/10.5281/zenodo.17709094). For certain questions, country- and year-specific EU statistics were used as a baseline for the scoring (Supplementary material, Table S1). Other questions and accompanying alternative answers were more descriptive and qualitative; hence, correlations based on these may be less objective. For both types of questions, precision in the baseline of alternative answers and the relevance and perception of the respondent most likely impacted which correlations were found and not found in this study.

### *4.2 Profitability and other sustainability aspects*

The majority of correlations were found among the spurs Profitability and Soil Management. Farms with permanent grassland only or no land reported 'non-applicable' for several questions in Soil management, causing this spur to be based on only a few questions and resultingly extreme values (raw data file - https://doi.org/10.5281/zenodo.17709094). Correlations with soil management should therefore be interpreted with caution. The same principle should be applied to the correlations with the water management spur, as its few questions (Supplementary material, Table S1) were often found hard to answer or not applicable (raw data file - https://doi.org/10.5281/zenodo.17709094).

Across all farms, profitability was negatively correlated with several spurs of the environmental dimension: Agri-environmental management, Landscape and heritage, NPK budget and Energy and carbon (Table 3). These negative correlations also occurred in one to two cases when analyses were undertaken in clusters 1, 3 and 4, wherein one negative correlation each was also found with the environmental spurs Soil management and Manure and fertilizer (Table 3). However, in cluster 3, Profitability was positively correlated with Agri-environmental management, Water management and the NPK budget (Table 3).

The number of negative correlations is demonstrative of the current conflict between economic gains and environmental sustainability, which affects all forms of livestock production (Pulina et al., 2021). From a legislative perspective, most operations occurring in this sector are conducted under the CAP and are thus intentionally structured to promote both profitability and environmental stewardship (Reg. EU 2021/2115). Nonetheless, these results emphasize the need for future innovative actions to be economically sustainable long-term as well. A potential example of this could be through the implementation of the production and consumption of renewable energy, in parallel with a major awareness of energy consumption within the animal farming sector. These solutions would not only aid in actively reducing the livestock sector's carbon footprint but also provide economic incentives through cost savings and enhanced energy efficiency (Elahi et al., 2019; Paris et al., 2022).

The results from this study suggest that, despite the political measures taking place (Reg. EU 2021/2115), Europe continues to present a non-negligible cost for the transition towards environmentally sustainable livestock production, for which the farmers leading the development are not paid in full. Necessary investments and measures to obtain environmentally sustainable agriculture were recently mapped on a national level in Sweden, where sustainable agriculture was defined as fulfilling all related directives at both the EU and national levels (LRF, 2023). The reported investments and measures were accomplished through calculations of the operational costs for this green transition (LRF, 2023). To the best of our knowledge, this Swedish report is the first of its kind in Europe. The yearly cost was estimated to correspond to 25% of the turnover rate in primary production but to only less than 6% of the food value at the end of the value chain at the retailer (LRF, 2023). Hence, obtaining sustainable food production is possible if the cost is shared among all community citizens, either as food consumers or taxpayers.

In the present study, the low scores of profitability were not always reflective of the farmers' experience (raw data file - https://doi.org/10.5281/zenodo.17709094). Generally, low scores for profitability could be due to the estimated amount of money per worked hour for the owner, which was compared to European statistics of labour cost (Eurostat, 2022). As no labour cost for agricultural enterprises was available in the statistics, the amount reported from the farms was compared to the cost in other industries. Additionally, currency rates could have played a role in biased financial results. Despite a low general scoring for profitability, the ranking of the spur among the farms should be the same, and the correlations should therefore not be biased by the low level.

The economic dimension presented a set of exclusively positive correlations with the social one, more specifically, among the spurs Profitability, Farm business resilience and Social wellbeing, both across all farms and cluster-wise (Table 3). The tight connection among the three is widely documented, with numerous studies investigating the underlying causes for these relations from different perspectives (Cradock-Henry, 2021; Nicholas-Davies et al., 2021; Perrin et al., 2020; Spiegel et al., 2021). For instance, in Perrin et al. (2020), the satisfaction levels of a farm's workers were employed as a subjective measurement to evaluate the farm's own resilience. Spiegel et al. (2021) described how a farmer's perception of their own business resilience could be linked to a more (or less) optimistic view that is dependent on the farm's dimensions, profitability, and limited (or greater) reliance on labour-intense farming. Moreover, farmers with a higher perceived resilience provided greater attention towards the provision of good working conditions for their employees than those with lower perceived resilience. In contrast, these farmers were more concerned about factors linked to the farm's profitability in the short-term, such as market price fluctuations, input prices and the reduction of CAP direct payments.

In this set of positive correlations, the only exception was represented by cluster 2, where Profitability and Social wellbeing were negatively correlated. This correlation could be explained by an interference from other factors, such as the average area dimension of the farms, which was the smallest among all the clusters, and the very high stocking rate (Table 2). The higher social scores of these farms could therefore be the intrinsic consequence of both their innovative nature and their type of production, characterized by strict biosecurity measures that require the constant presence of well-trained staff on the farm (Blagojevic et al., 2011). Alternatively, this result may suggest a current gap in European and national regulations regarding the assistance for the transition of innovative monogastric realities towards increased sustainability, in accordance with Adams et al. (2024).

Hence, each of these factors are integral to the long-term success of sustainable livestock production and therefore must be considered for future innovations within the field (Magnusson et al., 2022; Rivera-Huerta et al., 2019).

### 4.3 Covariation of spurs of environmental dimension

There were six positive correlations among spurs of the environmental dimension, such as Agri-environmental management, Energy and carbon, Landscape and heritage, System security and diversity, and the NPK budget (Table 3). Contradictorily, several of these correlations were absent or even negative when the data were analyzed cluster-wise (Table 3). This discrepancy between the analysis across all farms vs. cluster-wise indicates that the factors behind the spurs covary with the production system. This covariance is largely driven by the full range of productive systems involved, spanning from intensive monogastric farming to extensive grazing of cattle on semi-natural grasslands (Table 3).

Traditionally managed semi-natural grasslands in low-intensity livestock systems harbour an exceptional richness of many taxa (Eriksson, 2021; European Environment Agency, 2020). The species richness in these landscapes reflects a species pool from Pleistocene herbivore-structured environments, which, after the extinction of Pleistocene megafauna, was rescued by the introduction of domestic herbivores in pre-historic agriculture (Eriksson, 2021). Innovations promoting the grazing of traditionally, extensively managed semi-natural grasslands thus promote biodiversity. In the PG tool, management promoting biodiversity is found in spur Agri-environmental management, mainly driven by the activities such as intensity, habitat, management of pasture land, and management of other land (raw data file - https://doi.org/10.5281/zenodo.17709094). Accordingly, cluster 4, which was dominated by farms with extensive grazing of permanent grasslands, showed the numerically highest score for Agri-environmental management, although it was not significantly different from clusters 3 and 5 (Table S4). Such systems often include leys that can contribute to carbon sequestration (Fraser et al., 2022; Henryson et al., 2022; McAllister et al., 2020), which can partially explain the positive correlation between Agri-environmental management and Energy and carbon across all farms (Tables 3; S4). An exception to this result is represented by the small, extensive and ruminant-exclusive farms from cluster 3, which, despite high scoring for Agri-environmental management, presented a negative correlation between the two spurs. The explanation can be reconducted to the fact that this cluster often had a complex production with multiple land usage, such as grazing combined with orchards and forestry, and where a large proportion of both input and output energy was deployed for household consumption, hence the low scoring in the energy spur. This outcome reflects a limitation of the PG tool adaptation, which is designed for data collection from highly differentiated systems. Consequently, the correlations with energy and carbon in this specific cluster should be interpreted with caution. Extensive grazing also promotes other values, such as the maintenance and visibility of historical remains (Bele et al., 2018; Grove et al., 2020), resulting in a positive correlation between Agri-environmental management and Landscape and heritage across all farms (Table 3). Permanent, unfertilised grasslands prevent run-off and contribute to higher scores of Water management, which was the case for cluster 3, as shown in Table 3 (Milazzo et al., 2023).

Similar to the pattern found within the environmental dimension, social and environmental spurs presented six positive correlations when analyzed across all farms, whilst the same correlations were absent or opposite at the cluster level. An explanation for this could be drawn from the broad range of productive systems that constitute the ‘all farm’ group, characterized by extensive, semi-extensive and intensive systems with different levels of outdoor accessibility. In our study sample, such elements can be attributed not only to ruminant farms but also to monogastric farms because some of the units selected for the study had organic production, which requires outdoor access, as well as limited stocking densities compared to conventional systems (Åkerfeldt et al., 2021). Typically, animal farming systems with either partial or complete outdoor access are associated with high levels of animal welfare and low environmental pressure due to reduced external inputs, minimal land pressure and a reduced stocking rate compared to exclusively indoor realities (Ferreira et al., 2022; Monteiro et al., 2023; Rivero & Lee, 2022). On the other hand, the contrasting correlations obtained at the cluster level compared to analyses of all farms can be attributed to a greater internal homogeneity of the cluster groups. The uniformity of the scores among the farms of a single cluster, when present, can be seen as a reflection of the presence of common factors, such as management practices and environmental conditions, which can greatly influence animal welfare from nutritional, environmental and health perspectives (Rivero & Lee, 2022).

The discrepancy among scores reported by all farms and at the cluster level for the NPK budget seems to indicate that this parameter is less balanced in intensive farming systems. However, this may be partially biased, as the calculations did not consider the fertilizer stores at the start and end of the studied year, leading to a higher risk for under- or overestimations of the amount used per area unit in intensive farming.

The results provide additional value to the Nature Restoration Law, which was recently introduced to the current EU legislative framework with the aim of binding targets to restore large areas of degraded ecosystems (Reg. EU 2024/1991). For this reason, the number of grazing livestock on grassland habitat areas needs to dramatically increase (Hessle & Danielsson, 2024). Additionally, although the primary goal of the Nature Restoration Law is the promotion of biodiversity, additional effects will be an increased supply of European pasture-based meat and, according to the present study, several other positive effects on the environment and animal welfare.

### 4.4 Small-scaled diverse vs. large, specialised farm operations

In general, agriculture is moving towards increased specialization and size rationalization due to economies of size (Eurostat, 2024). The reverse, namely, small-scale, multi-functional operations with short value chains, is advocated by certain individuals as the direction we should go to achieve an environmentally sustainable animal production (Norton et al., 2022). Based on the results of this study, there is substantial reason to question this goal. Across all farms, there was a negative correlation between spur system security and diversity, describing multifunctionality, and spur profitability. Cluster 3 harboured the farms most similar to the advocated ideal with a small farm size, diverse production on the farm and a low stocking rate (Table 2). Cluster 3 also had the lowest score for Profitability, Social wellbeing and numerically for Farm business resilience (Table S4 and S5). It reached relatively high scores for the environmental spurs, but the highest environmental scores were predominantly found in cluster 4 along with a few in cluster 5, although these three clusters performed rather similarly (Tables S4 and S5). Cluster 4 harboured the farms with the largest agricultural area (Table 2) combined with the second highest scores for Profitability; however, it was not significantly different from clusters 1 and 2 (Table S4). The results indicate that high environmental performance is possible in both small farms and large farms with a low stocking density but combining environmental ambitions with an economically and socially sustainable production seems easier for larger farms. Nonetheless, this does not imply that smaller realities should disappear from the European panorama, notably because such farms represent active generators of knowledge and experiences useful for higher-level policy development (Knickel et al., 2018).

In parallel with size, another factor influencing a farm's sustainability is the geographical distribution of its livestock production. The farm operations with monogastrics in this study had, similar to most European farms (Neumann et al., 2009), often evolved from arable land and dairy farming systems in highly fertile areas. The smaller land requirements of monogastric farming compared to ruminants may have facilitated the transition of these systems from rural to peri-urban areas (EC Dir. 2007/43; EC Dir. 2008/120; Reg. EU 2020/464; Dupas et al., 2024). This can be confirmed by considering two activities driving spur soil management, intensity, which reflects farm animal density, and Habitat, which identifies the types of land present on the farm (Supplementary material and raw data file - https://doi.org/10.5281/zenodo.17709094).

In regions with high livestock density, new political measures are being taken with the expectation to decrease the production for environmental reasons, especially in relation to nitrogen surplus and methane emissions (LNV 2023; LNV, 2022; Rederink.dk, 2024). However, there is limited political attention towards stimulating sustainable farming systems in regions where more livestock are needed. This is testified by the EU's habitat directive highlighting the necessity for increased grazing in remote forest and mountain areas, e.g. Romania, Italy and Sweden (European Environment Agency, 2020; European Environment Agency, 2024; Seidl et al., 2022). The new Nature Restoration Law may change the discourse.

### 4.5 Animal welfare and profitability

In monogastric-dominated cluster 1, which had the highest score for profitability, a positive correlation between animal welfare and profitability was found (Table 3). The result was expected, as the innovative business model for these farms, representing seven PHs, included several improvements for animal welfare (List 1, Supplementary material). Nonetheless, the r value of the correlation indicated a very low strength of the correlation. A potential explanation for this could be related to the rigorous biosecurity measures that monogastric systems are typically required to follow to avoid infections (EFSA AHAW Panel et al., 2021; de

Vos & Elbers, 2024). Such practices can lead to a trade-off, where improved efficiency and animal health may come at the cost of reduced opportunity to perform natural behaviours that would often be favoured by an outdoor environment (Maes et al., 2021). The Animal welfare and Profitability correlation resulted negative in ruminant-dominated cluster 3, which presented the lowest score for Profitability among all the clusters. The correlation could be explained by poor profitability hampering investments, e.g. loose housing barns instead of tied-up systems for dairy cows, which could allow the animals to better express their natural behaviour (Spigarelli et al., 2020). In contrast, in beef cattle-dominated cluster 4, which had a high score for Profitability, the correlation between Animal welfare and Profitability was positive (Table 3).

## 5. Conclusions

In conclusion, relationships among various aspects of sustainability are not consistent across production systems. When analysed across all the investigated farms, several spurs of the environmental dimension were positively correlated with each other. The positive covariation of the spurs of environmental dimension could be explained by differences in production systems from intensive monogastrics to extensive ruminants for the whole dataset. However, when analysed cluster-wise in more homogenous groups of farms, these correlations could be absent or even negative. Thus, the range and heterogeneity of farms represent an element of major importance for the results when investigating relationships among various aspects of sustainability in agriculture. When analysed across all farms, many of the environmental spurs were negatively correlated with spur profitability. These negative correlations illustrate how the farmers at the forefront of the green transition, such as the ones selected for our study, are bearing an excessively large transition cost to remain economically competitive. The positive correlations among the spurs social well-being and farm business resilience further confirm that if the transition continues to be paid by the innovative farmers at the front, their social well-being will decrease, eventually leading to some quitting their businesses. A comparison of cluster-wise correlations of small-sized vs. large-sized farm groups with similar environmental performances showed a positive correlation between environmental spurs and profitability for the large farms, in contrast to a negative correlation among the same spurs for the small farms. Such a result indicates that, within the current legislative framework, a future livestock production combining environmental, economic and social sustainability would be easier to achieve with larger rather than smaller farm operations.

Among the major implications from this study, it is possible to highlight both the common and the diverging patterns across different production systems, indicating that certain sustainability dynamics may extend beyond species- or sector-specific contexts. From a theoretical perspective, this research underlines the value of integrated, indicator-based approaches to adequately capture the complexity of sustainability in livestock farming. In terms of policy implications, the results can inform the development of more tailored and flexible sustainability support schemes within the CAP framework and assist advisory services and farmers' organizations in identifying synergies and tensions across sustainability dimensions. Additionally, stakeholders may benefit from the employed methodological approach, which provides a structured tool for assessing farm-level sustainability by combining qualitative and quantitative factors.

However, the study has several limitations. First, despite a relatively large and geographically diverse sample, the size remains limited, especially when the sample is subdivided by species or production system. Second, the cross-sectional nature of the data restricts causal inference and the ability to detect temporal changes. Third, applying a single analytical framework to fundamentally different livestock sectors can pose interpretative challenges, even with standardisation efforts in place. For instance, employing LSU/ha to describe farm-level stocking intensity may result in seemingly disproportionate values for monogastrics compared with ruminants; however, this stems from the need to adopt a common unit across all systems and should not be interpreted as an absolute measure of animal density, as both LSU and UAA are derived and indirect metrics strongly influenced by the type of livestock management system (Ramos-García et al., 2022). Future research should consider sector-specific analyses to better capture the unique characteristics and priorities of each livestock system. Furthermore, a more in-depth exploration of socioeconomic and organizational dimensions—only partially addressed here—would contribute to a more comprehensive understanding of sustainability drivers. Longitudinal studies would also improve the capacity to identify causal links between sustainability dimensions and farm performance over time.

Taken together, our study demonstrates that using a single questionnaire for farms with such differences in livestock species, geographic conditions and sustainability focuses can be challenging. Nonetheless, although no universal key can unlock a sustainable future for all types of animal farming, understanding the high heterogeneity of realities shaping the sector, combined with the involvement of the actors currently leading the transition, represents a crucial first step towards a more environmentally, economically and socially sustainable livestock sector.

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## Author contributions

E. Diaz Vicuna: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, N. Adams: Data curation, Formal analysis, Investigation, Visualization, Writing – review & editing, L.G. Smith: Data curation, Investigation, Writing – review & editing, Funding acquisition, M. Durand, C. van Wagenberg, E. Caron, A. van den Pol-van Dasselaar, L. Baumgart, S. Schetelat, M. Sandor, A. Gliga, S. Espagnol, H. M-L. Andersen, R. Borek, P. Jurga, N. van Leuffen, J.L.T. Heerkens, J. Yngvesson, A. Oosterwijk, J. Stokes, C. Forte: Investigation, Data curation, Writing – review & editing, A. Hessle: Conceptualization, Validation, Investigation, Data curation, Writing – review & editing, Supervision, Project administration.

All authors agree to be accountable for all aspects of the work.

## Disclosure statement

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## Data availability statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.17709094.

## Ethics statement

This research was conducted in accordance with the ethical guidelines established by the Coordination Team with input from an independent Ethics Advisor for the H2020 PATHWAYS project (grant agreement No 101000395). Through this process, we adhered to the principles outlined in the European Convention on Human Rights and the European Charter of Fundamental Rights to ensure ethically and socially responsible research and dissemination methods, particularly concerning informed consent and data anonymization. Informed consent was obtained through a written formal consent form provided in advance of data collection, which outlined the study purpose, voluntary participation, data handling, anonymization and withdrawal rights.

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