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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 Schetelatⁱ, Mignon Sandor^j , Adrian Gliga^j, Sandrine Espagnol^k, Heidi Mai-Lis Andersen^l,
Robert Borek^m , Piotr Jurgaⁿ , Noa van Leuffen^g, Jasper L.T. Heerkens^g, Jenny Yngvesson^o ,
Annabel Oosterwijk^e , Jessica Stokes^p, Claudio Forte^a  and Anna Hesse^o 

^aUniversity of Turin, Veterinary Sciences, Grugliasco, Italy; ^bUniversity of Reading, School of Agriculture, Policy and Development, Reading, United Kingdom; ^cÖkomodell-Region Landkreis Waldeck-Frankenberg, Korbach, Germany; ^dSwedish University of Agricultural Sciences, Biosystems and Technology, Lomma, Sweden; ^eWageningen Social & Economic Research, Part of Wageningen University & Research, Wageningen, the Netherlands; ^fITAVI, Rennes, France; ^gAeres University of Applied Sciences, Dronten, the Netherlands; ^hResearch Institute of Organic Agriculture FiBL, Frick, Switzerland; ⁱFrench Livestock Institute, Le Rheu, France; ^jUniversity of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Faculty of Agriculture, Cluj-Napoca, Romania; ^kFrench Institute for Pig and Pork Industry, Pacé, France; ^lInnovation Centre for Organic Farming, Livestock, Aarhus N, Denmark; ^mInstitute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB), Department of Bioeconomics and Agrometeorology, Puławy, Poland; ⁿInstitute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB), Department of Geomatics, Puławy, Poland; ^oSwedish University of Agricultural Sciences, Applied Animal Science and Welfare, Skara, Sweden; ^pRoyal Agricultural University, Cirencester, United Kingdom

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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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

CONTACT Elena Diaz Vicuna  elena.diazvicuna@unito.it  University of Turin, Veterinary Sciences, Largo Paolo Braccini 2, Grugliasco, TO, 10095, Italy

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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

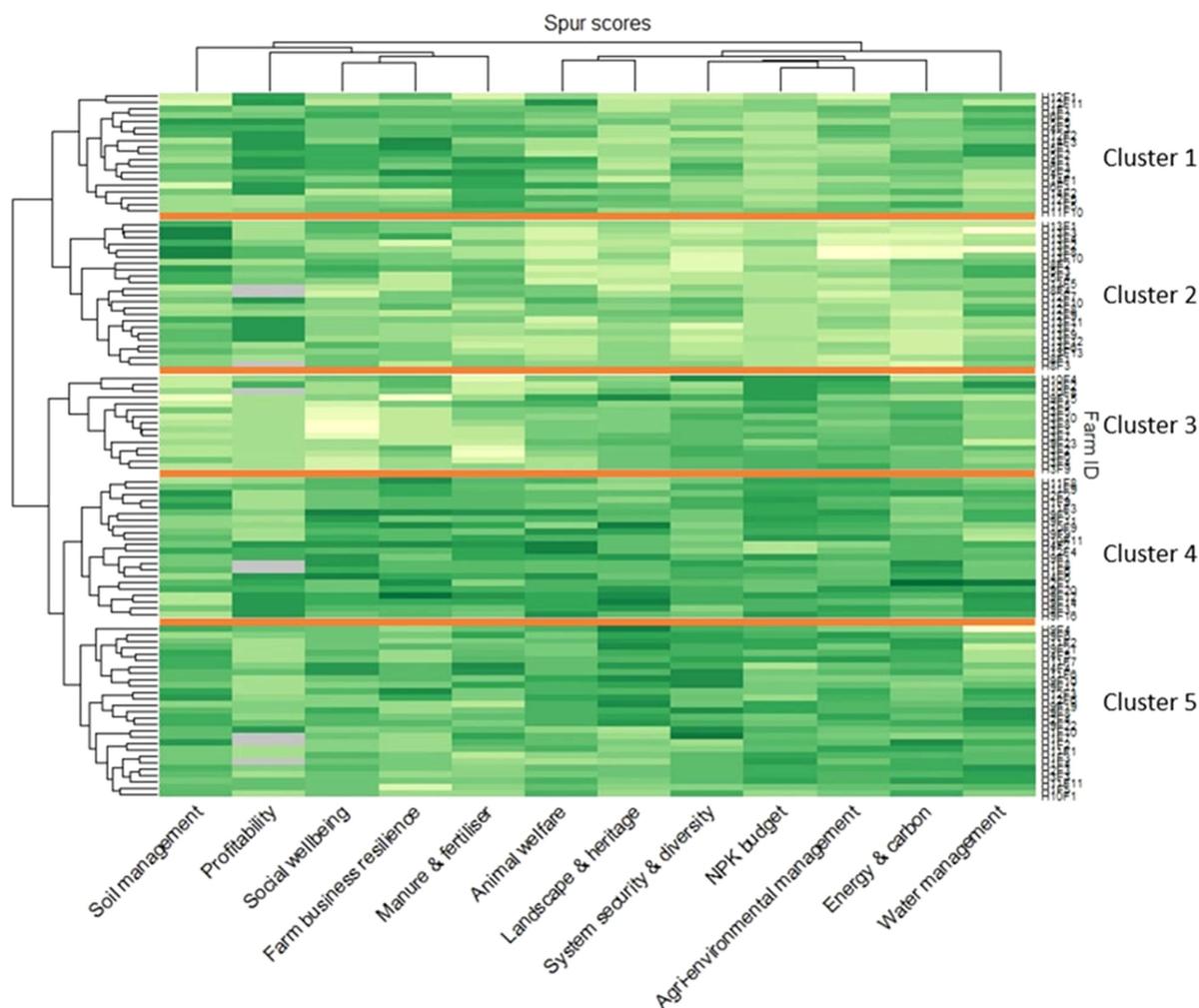


Figure 2. Heatmap of standardised values (spur mean is 0, variance is 1) of the different spur scores; each column identifies a single spur, each row identifies a single farm, and each cell represents a specific farm's spur score. The colour intensity of the cells across a column reflects the distance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

Cluster	Livestock type (% and number of farms)								Farm size (ha)		Stocking rate (LU/ha)	
	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*		
Landscape & heritage	Energy & carbon	0.55**			-0.37*		
	Soil management	-0.03*		-0.44**		-0.22*	0.22*
	Water management				-0.45*		
	Manure & fertiliser		0.37***	-0.33**			
Soil management	NPK budget	0.50***		-0.25*			-0.04**
	Energy & carbon	0.38**					-0.24**
	Water management		0.47*				
Water management	Manure & fertiliser					-0.10*	
	NPK budget	-0.23**			-0.31**		-0.45***
	Energy & carbon	-0.09**			0.22**		-0.17*
	Manure & fertiliser		-0.49*		-0.27*		-0.41*
Manure & fertiliser	NPK budget			0.56***			
	Energy & carbon						
	NPK budget			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***					
Profitability	Farm business resilience						
	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*	
Social wellbeing	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**
	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***	
System security & diversity	NPK budget				0.39**		
	Energy & carbon			0.43*	-0.67**		
	Agri-environmental management	0.52***					-0.31*
	Landscape & heritage	0.56***		0.54**			
Profitability	Soil management	-0.13**		-0.40**			
	Water management						-0.39**
	Manure & fertiliser						0.54**
	NPK budget	0.55***					
	Energy & carbon	0.47***					
	Agri-environmental management	-0.22**	-0.31*		0.58**		
	Landscape & heritage	-0.21**	-0.20*		-0.43*	0.31*	
Farm business resilience	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*		
System security & diversity	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*
Profitability	NPK budget			-0.08*			-0.37***
	Energy & carbon				-0.42*		-0.18**
	Animal welfare	0.42**		0.52***			
System security & diversity	Social wellbeing				0.36*		
	Animal welfare		<0.01**		-0.32*	0.55**	
Farm business resilience	Social wellbeing	0.18**		-0.53***	0.50*		
	Animal welfare				-0.41**		
System security & diversity	Social wellbeing				0.46**		
	Animal welfare	0.56*	0.47**				

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.

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ORCID

Elena Diaz Vicuna  0000-0002-0197-518X
Nina Adams  0000-0001-5699-7063
Laurence Smith  0000-0002-9898-9288
Coen van Wagenberg  0000-0002-8813-3742
Agnes van den Pol-van Dasselaar  0000-0002-9070-9704
Lukas Baumgart  0000-0002-5858-5123
Mignon Sandor  0000-0002-2007-992X
Robert Borek  0000-0001-9414-3181
Piotr Jurga  0000-0002-9188-1565
Jenny Yngvesson  0000-0003-3123-2229
Annabel Oosterwijk  0009-0004-5406-4189
Claudio Forte  0000-0002-0060-3851
Anna Hessle  0000-0002-5195-1186

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.

References

- Adams, N., Sans, A., Trier Kreutzfeldt, K. E., Arias Escobar, M. A., Oudshoorn, F. W., Bolduc, N., Aubert, P. M., & Smith, L. G. (2024). Assessing the impacts of EU agricultural policies on the sustainability of the livestock sector: A review of the recent literature. *Agriculture and Human Values*, 42, 1–20. <https://doi.org/10.1007/s10460-024-10595-y>
- Åkerfeldt, M. P., Gunnarsson, S., Bernes, G., & Blanco-Penedo, I. (2021). Health and welfare in organic livestock production systems—A systematic mapping of current knowledge. *Organic Agriculture*, 11(1), 105–132. <https://doi.org/10.1007/s13165-020-00334-y>
- Arvidsson, S. K., Hansson, H., Sonesson, U., & Gunnarsson, S. (2020). Research on environmental, economic, and social sustainability in dairy farming: A systematic mapping of current literature. *Sustainability*, 12(14), 5502. <https://doi.org/10.3390/su12145502>
- Arvidsson, S. K., Hansson, H., Sonesson, U., & Gunnarsson, S. (2021). A systematic mapping of current literature on sustainability at farm-level in beef and lamb meat production. *Sustainability*, 13(5), 2488. <https://doi.org/10.3390/su13052488>
- Bele, B., Norderhaug, A., & Sickel, H. (2018). Localized agri-food systems and biodiversity. *Agriculture*, 8(2), 22. <https://doi.org/10.3390/agriculture8020022>
- Binder, C. R., Feola, G., & Steinberger, J. K. (2010). Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environmental Impact Assessment Review*, 30(2), 71–81. <https://doi.org/10.1016/j.eiar.2009.06.002>
- Blagojevic, B., Nesbakken, T., Alvseike, O., Vågsholm, I., Antic, D., Johler, S., Houf, K., Meemken, D., Nastasijevic, I., Vieira-Pinto, Madalena, Antunovic, B., Georgiev, M., & Alban, L. (2021). Drivers, opportunities, and challenges of the European risk-based meat safety assurance system. *Food Control*, 124, 107870. <https://doi.org/10.1016/j.foodcont.2021.107870>
- Braun, G., & Ghosh, K. (2020). *Transforming food and agriculture to achieve the sustainable development goals (SDGs): Good practices from FAO/GEF projects around the world*. FAO. <https://doi.org/10.4060/ca8768en>
- Caccialanza, A., Cerrato, D., & Galli, D. (2023). Sustainability practices and challenges in the meat supply chain: A systematic literature review. *British Food Journal*, 125(12), 4470–4497. <https://doi.org/10.1108/BFJ-10-2022-0866>
- Coteur, I., Wustenberghs, H., Debruyne, L., Lauwers, L., & Marchand, F. (2020). How do current sustainability assessment tools support farmers' strategic decision making? *Ecological Indicators*, 114, 106298. <https://doi.org/10.1016/j.ecolind.2020.106298>
- Council Directive 2007/43/EC of 28 June 2007 laying down minimum rules for the protection of chickens kept for meat production. (2019). <http://data.europa.eu/eli/EFSA Journal, 2021/2007/43/2019-12-14>
- Council Directive 2008/120/EC of 18 December 2008 laying down minimum standards for the protection of pigs. (2019). <http://data.europa.eu/eli/dir/2008/120/2019-12-14>
- Cradock-Henry, N. A. (2021). Linking the social, economic, and agroecological: A resilience framework for dairy farming. *Ecology and Society*, 26(1), 3. <https://doi.org/10.5751/ES-12122-260103>
- Dawkins, M. S. (2016). Animal welfare and efficient farming: Is conflict inevitable? *Animal Production Science*, 57(2), 201–208. <https://doi.org/10.1071/AN15383>
- de Mendiburu, F. (2023). *Agricolae: Statistical procedures for agricultural research (version 1.3-7)*. R Package.
- de Vos, C. J., & Elbers, A. R. (2024). Quantitative risk assessment of wind-supported transmission of highly pathogenic avian influenza virus to Dutch poultry farms via fecal particles from infected wild birds in the environment. *Pathogens*, 13(7), 571. <https://doi.org/10.3390/pathogens13070571>
- Di Vita, G., Zanchini, R., De Cianni, R., Pippinato, L., Mancuso, T., & Brun, F. (2024). Sustainable livestock farming in the European Union: A study on beef farms in NUTS 2 regions. *Sustainability*, 16(3), 1098. <https://doi.org/10.3390/su16031098>
- Dumont, B., Ryschawy, J., Duru, M., Benoit, M., Chatellier, V., Delaby, L., Donnars, C., Dupraz, P., Lemauiel-Lavenant, S., Méda, B., Vollet, D., & Sabatier, R. (2019). Associations among goods, impacts and ecosystem services provided by livestock farming. *Animal*, 13(8), 1773–1784. <https://doi.org/10.1017/S1751731118002586>
- Dupas, M. C., Pinotti, F., Joshi, C., Joshi, M., Thanapongtharm, W., Dhingra, M., Blake, D., Tomley, F., Gilbert, M., & Fournié, G. (2024). Spatial distribution of poultry farms using point pattern modelling: A method to address livestock environmental impacts and disease transmission risks. *PLoS Computational Biology*, 20(10), e1011980. <https://doi.org/10.1371/journal.pcbi.1011980>

- EFSA AHAW Panel (EFSA Panel on Animal Health and Welfare), Nielsen, S. S., Alvarez, J., Bicout, D. J., Calistri, P., Canali, E., Drewe, J. A., Garin-Bastuji, B., Gonzales Rojas, J. L., Herskin, M., Miranda Chueca, M. A., Michel, V., Padalino, B., Pasquali, P., Roberts, H. C., Sihvonen, L. H., Spoolder, H., Stahl, K., Velarde, A., ... Schmidt, C. G. (2021). African swine fever and outdoor farming of pigs. *EFSA Journal*, 19(6), e06639. <https://doi.org/10.2903/j.efsa.2021.6639>
- Elahi, E., Weijun, C., Jha, S. K., & Zhang, H. (2019). Estimation of realistic renewable and non-renewable energy use targets for livestock production systems utilising an artificial neural network method: A step towards livestock sustainability. *Energy*, 183, 191–204. <https://doi.org/10.1016/j.energy.2019.06.084>
- Eriksson, O. (2021). The importance of traditional agricultural landscapes for preventing species extinctions. *Biodiversity and Conservation*, 30(5), 1341–1357. <https://doi.org/10.1007/s10531-021-02145-3>
- Eriksson, O. (2022). Coproduction of food, cultural heritage and biodiversity by livestock grazing in Swedish semi-natural grasslands. *Frontiers in Sustainable Food Systems*, 6, 801327. <https://doi.org/10.3389/fsufs.2022.801327>
- European Union. Commission Implementing Regulation (EU) 2020/464 of 26 March 2020 laying down certain rules for the application of Regulation (EU) 2018/848 of the European Parliament and of the Council as regards the documents needed for the retroactive recognition of periods for the purpose of conversion, the production of organic products and information to be provided by Member States. (2021). http://data.europa.eu/eli/reg_impl/2020/464/2021-11-25
- European Environment Agency. (2020). State of the nature in EU (Report 10) Estimation of Annex I habitats' areas to be improved and area to be recreated per region. Retrieved November 22, 2024, from Available at <https://www.eea.europa.eu/publications/state-of-nature-in-the-eu-2020>
- European Environment Agency. (2024). Explore nature reporting data: Estimation of Annex I habitats' areas to be improved and area to be recreated per region. Retrieved November 22, 2024, from https://tableau-public.discomap.eea.europa.eu/views/SONrestoration/Story1/d14f11e7-687d-4ccf-acd2-18f374b89c44/a5301d17-b660-4996-8792-bd4858ecf538?%3Adisplay_count=n&%3AshowVizHome=n
- Eurostat. (2022). Farmers and the agricultural labour force – statistics. Eurostat. Retrieved February 20, 2024, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_and_the_agricultural_labour_force_-_statistics.
- Eurostat. (2024). Glossary: Livestock unit (LSU). Retrieved November 19, 2024, from [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_\(LSU\)](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Livestock_unit_(LSU))
- FAO. (2014). *Developing sustainable food value chains – Guiding principles*.
- Ferreira, V. H. B., Simoni, A., Germain, K., Leterrier, C., Lansade, L., Collin, A., Mignon-Grasteau, S., Le Bihan-Duval, E., Guettier, E., Leruste, H., Løvlie, H., Calandreau, L., & Guesdon, V. (2022). Foraging behavior shows individual consistency over time, and predicts range use in slow-growing free-range male broiler chickens. *Frontiers in Veterinary Science*, 9, 814054. <https://doi.org/10.3389/fvets.2022.814054>
- Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., ... Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, 478(7369), 337–342. <https://doi.org/10.1038/nature10452>
- Fraser, M. D., Vallin, H. E., & Roberts, B. P. (2022). Animal board invited review: Grassland-based livestock farming and biodiversity. *Animal*, 16(12), 100671. <https://doi.org/10.1016/j.animal.2022.100671>
- Galdeano-Gómez, E., Aznar-Sánchez, J. A., Pérez-Mesa, J. C., & Piedra-Muñoz, L. (2017). Exploring synergies among agricultural sustainability dimensions: An empirical study on farming systems in Almería (Southeast Spain). *Ecological Economics*, 140, 99–109. <https://doi.org/10.1016/j.ecolecon.2017.05.001>
- García-Díez, J., Gonçalves, C., Grispoldi, L., Cenci-Goga, B., & Saraiva, C. (2021). Determining food stability to achieve food security. *Sustainability*, 13(13), 7222. <https://doi.org/10.3390/su13137222>
- Gault, F. (2018). Defining and measuring innovation in all sectors of the economy. *Research Policy*, 47, 617–622. <https://doi.org/10.1016/j.respol.2018.01.007>
- Gerrard, C. L., Smith, L. G., Pearce, B., Padel, S., Hitchings, R., Measures, M., & Cooper, N. (2012). Public goods and farming. In E. Lichtfouse (Ed.), *Farming for food and water security (sustainable agriculture reviews)* (Vol. 10, pp. 1–22). Springer. https://doi.org/10.1007/978-94-007-4500-1_1
- Grove, R., Evans Pim, J., Serrano, M., Cidrás, D., Viles, H., & Sanmartín, P. (2020). Pastoral stone enclosures as biological cultural heritage: Galician and Cornish examples of community conservation. *Land*, 9(1), 9. <https://doi.org/10.3390/land9010009>
- Gu, Z. (2022). Complex heatmap visualization. *iMeta*, 1(3), e43. <https://doi.org/10.1002/imt2.43>
- Gu, Z., Eils, R., & Schlesner, M. (2016). Complex heatmaps reveal patterns and correlations in multidimensional genomic data. *Bioinformatics*, 32(18), 2847–2849. <https://doi.org/10.1093/bioinformatics/btw313>
- Gunnarsson, S., Arvidsson, S. K., Göransson, L., Hansson, H., & Sonesson, U. (2020a). Systematic mapping of research on farm-level sustainability in egg and chicken meat production. *Sustainability*, 12, 3033. <https://doi.org/10.3390/su12073033>
- Gunnarsson, S., Arvidsson, S. K., Wallgren, T., Hansson, H., & Sonesson, U. (2020b). A systematic mapping of research on sustainability dimensions at farm-level in pig production. *Sustainability*, 12, 4352. <https://doi.org/10.3390/su12114352>
- Guyomard, H., Bouamra-Mechemache, Z., Chatellier, V., Delaby, L., Détang-Dessendre, C., Peyraud, J. L., & Requillart, V. (2021). Why and how to regulate animal production and consumption: The case of the European Union. *Animal*, 15, 100283. <https://doi.org/10.1016/j.animal.2021.100283>
- Harrell, F. E., Jr., & Dupont, C. (2024). *HMISC: Harrell miscellaneous*. R package version 4.0. Retrieved February 13, 2024, from <https://hbiostat.org/R/Hmisc/>

- Henryson, K., Meurer, K. H., Bolinder, M. A., Kätterer, T., & Tidåker, P. (2022). Higher carbon sequestration on Swedish dairy farms compared with other farm types as revealed by national soil inventories. *Carbon Management*, 13(1), 266–278. <https://doi.org/10.1080/17583004.2022.2074315>
- Hessle, A., & Danielsson, R. (2024). Cattle population required for favorable conservation status of management-dependent semi-natural grasslands and forests, and associated increase in enteric methane emissions. *Journal for Nature Conservation*, 78, 126571. <https://doi.org/10.1016/j.jnc.2024.126571>
- Kheiralipour, K., Rafiee, S., Karimi, M., Nadimi, M., & Paliwal, J. (2024). The environmental impacts of commercial poultry production systems using life cycle assessment: A review. *World's Poultry Science Journal*, 80(1), 33–54. <https://doi.org/10.1080/00439339.2023.2250326>
- Kiran, B. R., Prasad, M. N. V., & Mohan, S. V. (2023). Farm to fork: Sustainable agrifood systems. In *Sustainable and circular management of resources and waste towards a green deal* (pp. 25–38). Elsevier. <https://doi.org/10.1016/B978-0-323-95278-1.00012-7>
- Knickel, K., Redman, M., Darnhofer, I., Ashkenazy, A., Chebach, T. C., Šūmane, S., Tisenkopfs, T., Zemeckis, R., Atkociuniene, V., Rivera, M., Strauss, A., Kristensen, L. S., Schiller, S., Koopmans, M. E., & Rogge, E. (2018). Between aspirations and reality: Making farming, food systems and rural areas more resilient, sustainable and equitable. *Journal of Rural Studies*, 59, 197–210. <https://doi.org/10.1016/j.jrurstud.2017.04.012>
- Lai, L., & Kumar, S. (2020). A global meta-analysis of livestock grazing impacts on soil properties. *PLoS One*, 15(8), e0236638. <https://doi.org/10.1371/journal.pone.0236638>
- Leinonen, I., & Kyriazakis, I. (2016). How can we improve the environmental sustainability of poultry production? *Proceedings of the Nutrition Society*, 75(3), 265–273. <https://doi.org/10.1017/s0029665116000094>
- Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., Simpson, D., Sutton, M. A., de Vries, W., & Westhoek, H. (2015). Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication, and biodiversity. *Environmental Research Letters*, 10(11), 115004. <https://doi.org/10.1088/1748-9326/10/11/115004>
- Leroy, F., Abraini, F., Beal, T., Dominguez-Salas, P., Gregorini, P., Manzano, P., Rowntree, J., & Van Vliet, S. (2022). Animal board invited review: Animal source foods in healthy, sustainable, and ethical diets – An argument against drastic limitation of livestock in the food system. *Animal*, 16(3), 100457. <https://doi.org/10.1016/j.animal.2022.100457>
- LNV. (2022). *Ontwikkeldocument Nationaal Programma Landelijk Gebied*. Ministerie van Landbouw. Natuur en Voedselkwaliteit. Retrieved January 8, 2025, from Available at: <https://www.rijksoverheid.nl/documenten/publicaties/2022/11/25/ontwikkeldocument-nationaal-programma-landelijk-gebied>
- LNV. (2023). Regeling van de Minister voor Natuur en Stikstof, nr. WJZ/27312934, houdende regels voor de verstrekking van subsidie voor het sluiten van veehouderijlocaties met piekbelasting op natuurgebieden (Landelijke beëindigingsregeling veehouderijlocaties met piekbelasting). Staatscourant nr, 15029. Retrieved January 13, 2025, from <https://zoek.officielebekendmakingen.nl/stcrt-2023-15029.pdf>
- Lovarelli, D., Bacenetti, J., & Guarino, M. (2020). A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production? *Journal of Cleaner Production*, 262, 121409. <https://doi.org/10.1016/j.jclepro.2020.121409>
- Lovarelli, D., Bava, L., Zucali, M., D'Imporzano, G., Adani, F., Tamburini, A., & Sandrucci, A. (2019). Improvements to dairy farms for environmental sustainability in Grana Padano and Parmigiano Reggiano production systems. *Italian Journal of Animal Science*, 18(1), 1035–1048. <https://doi.org/10.1080/1828051X.2019.1651452>
- LRF. (2023). *Costs of the green transition of agriculture: A Swedish example. An analysis from the federation of Swedish farmers regarding the total costs of the green transition in agriculture*. Retrieved January 8, 2025, from Available at: <https://www.lrf.se/nyheter/ny-rapport-fran-lrf-20-miljarder-for-att-stalla-om-sveriges-jordbruk/>
- Maes, D., Kyriazakis, I., Chantziaras, I., Van Limbergen, T., & Christensen, J. P. (2021). Bacterial diseases in pigs and poultry: Occurrence, epidemiology, and biosecurity measures. In *Advancements and technologies in pig and poultry bacterial disease control* (pp. 25–51). Academic Press. <https://doi.org/10.1016/B978-0-12-818030-3.00001-5>
- Magnusson, U., Boqvist, S., Doyle, R., & Robinson, T. (2022). *Animal health and welfare for sustainable livestock systems*. Global Agenda for Sustainable Livestock. Retrieved December 23, 2024, from <https://hdl.handle.net/10568/125970>
- Marchand, F., Debruyne, L., Triste, L., Gerrard, C., Padel, S., & Lauwers, L. (2014). Key characteristics for tool choice in indicator-based sustainability assessment at farm level. *Ecology and Society*, 19(3):46. <https://doi.org/10.5751/ES-06265-190319>
- Marta-Costa, A. A., & Silva, E. (2013). Approaches for sustainable farming systems assessment. In A. Marta-Costa, & E. Soares da Silva (Eds.), *Methods and procedures for building sustainable farming systems* (pp. 21–29) (pp. 21–29). Springer. https://doi.org/10.1007/978-94-007-5003-6_3
- Martin, G., Barth, K., Benoit, M., Brock, C., Destruel, M., Dumont, B., Grillot, M., Hübner, S., Magne, M. -A., Moerman, M., Mosnier, C., Parsons, D., Ronchi, B., Schanz, L., Steinmetz, L., Werne, S., Winckler, C., & Primi, R. (2020). Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review. *Agricultural Systems*, 181, 102821. <https://doi.org/10.1016/j.agsy.2020.102821>
- McAllister, T. A., Stanford, K., Chaves, A. V., Evans, P. R., de Souza Figueiredo, E. E., & Ribeiro, G. (2020). Nutrition, feeding, and management of beef cattle in intensive and extensive production systems. In *Animal Agriculture* (pp. 75–98). Academic Press. <https://doi.org/10.1016/B978-0-12-817052-6.00005-7>

- Milazzo, F., Francksen, R. M., Zavattaro, L., Abdalla, M., Hejduk, S., Enri, S. R., Pittarello, M., Newell Price, P., Schils, R. L. M., Smith, P., & Vanwalleggem, T. (2023). The role of grassland for erosion and flood mitigation in Europe: A meta-analysis. *Agriculture, Ecosystems & Environment*, 348, 108443. <https://doi.org/10.1016/j.agee.2023.108443>
- Monteiro, M. S., Muro, B. B., Carnevale, R. F., Poor, A. P., Araújo, K. M., Viana, C. H., Almond, G. W., Moreno, A. M., Garbossa, C. A. P., & Leal, D. F. (2023). The beneficial effects of providing prepartum sows with nesting materials on farrowing traits, piglet performance, and maternal behavior: A systematic review and meta-analysis. *Applied Animal Behaviour Science*, 259, 105795. <https://doi.org/10.1016/j.applanim.2023.105795>
- Muscat, A., De Olde, E. M., de Boer, I. J., & Ripoll-Bosch, R. (2020). The battle for biomass: A systematic review of food-feed-fuel competition. *Global Food Security*, 25, 100330. <https://doi.org/10.1016/j.gfs.2020.100330>
- Neumann, K., Elbersen, B. S., Verburg, P. H., Staritsky, I., Pérez-Soba, M., de Vries, W., & Rienks, W. A. (2009). Modelling the spatial distribution of livestock in Europe. *Landscape Ecology*, 24, 1207–1222. <https://doi.org/10.1007/s10980-009-9351-3>
- Nicholas-Davies, P., Fowler, S., Midmore, P., Coopmans, I., Draganova, M., Pettitt, A., & Senni, S. (2021). Evidence of resilience capacity in farmers' narratives: Accounts of robustness, adaptability, and transformability across five different European farming systems. *Journal of Rural Studies*, 88, 388–399. <https://doi.org/10.1016/j.jrurstud.2021.03.013>
- Nigmann, T., Dax, T., & Hovorka, G. (2018). Applying a social-ecological approach to enhancing provision of public goods through agriculture and forestry activities across the European Union. *Studies in Agricultural Economics*, 120(1), 1–7. <https://doi.org/10.7896/j.1713>
- Norton, L., Maskell, L., McVittie, A., Smith, L., Wagner, M., Waterton, C., & Watson, C. (2022). Learning from innovative practitioners: Evidence for the sustainability and resilience of pasture-fed livestock systems. *Frontiers in Sustainable Food Systems*, 6, 1012691. <https://doi.org/10.3389/fsufs.2022.1012691>
- Pahmeyer, C., & Britz, W. (2022). Life cycle sustainability assessment of European beef production systems based on a farm-level optimization model. *Journal of Cleaner Production*, 376, 134285. <https://doi.org/10.1016/j.jclepro.2022.134285>
- Paraskevopoulou, C., Theodoridis, A., Johnson, M., Ragkos, A., Arguile, L., Smith, L., Vlachos, D., & Arsenos, G. (2020). Sustainability assessment of goat and sheep farms: A comparison between European countries. *Sustainability*, 12(8), 3099. <https://doi.org/10.3390/su12083099>
- Paris, B., Vadorou, F., Tyris, D., Balafoutis, A. T., Vaiopoulos, K., Kyriakarakos, G., Manolakos, D., & Papadakis, G. (2022). Energy use in the EU livestock sector: A review recommending energy efficiency measures and renewable energy sources adoption. *Applied Sciences*, 12(4), 2142. <https://doi.org/10.3390/app12042142>
- Perrin, A., San Cristobal, M., Milestad, R., & Martin, G. (2020). Identification of resilience factors of organic dairy cattle farms. *Agricultural Systems*, 183, 102875. <https://doi.org/10.1016/j.agsy.2020.102875>
- Peyraud, J. L., & MacLeod, M. (2020). *Study on the future of EU livestock: How to contribute to a sustainable agricultural sector? Executive summary*. Publications Office of the European Union. <https://doi.org/10.2762/810306>
- Post, P. M., Hogerwerf, L., Bokkers, E. A., Baumann, B., Fischer, P., Rutledge-Jonker, S., Hilderink, H., Hollander, A., Hoogsteen, M. J. J., Liebman, A., Mangen, M. J. J., Manuel, H. J., Mughini-Gras, L., Poll, R., Posthuma, L., Pul, A., Rutgers, M., Schmitt, H., van Steenbergen, J., ... de Boer, I. J. (2020). Effects of Dutch livestock production on human health and the environment. *Science of the Total Environment*, 737, 139702. <https://doi.org/10.1016/j.scitotenv.2020.139702>
- Pulina, G., Acciaro, M., Atzori, A. S., Battacone, G., Crovetto, G. M., Mele, M., Pirlo, G., & Rassu, S. P. G. (2021). Animal board invited review—Beef for future: Technologies for a sustainable and profitable beef industry. *Animal*, 15(11), 100358. <https://doi.org/10.1016/j.animal.2021.100358>
- Pykälä, J. (2005). Cattle grazing increases plant species richness of most species trait groups in mesic semi-natural grasslands. *Plant Ecology*, 175, 217–226. <https://doi.org/10.1007/s11258-004-0167-y>
- Ramos-García, M., Guzmán, G. I., & de Molina, M. G. (2022). Organic management of cattle and pigs in Mediterranean systems: Energy efficiency and ecosystem services. *Agronomy for Sustainable Development*, 42(6), 111. <https://doi.org/10.1007/s13593-022-00842-z>
- R. Core Team. (2023). R: A language and environment for statistical computing, *R Foundation for Statistical Computing*. Rederink.dk (Danish government official website). (2024). *Aftale om et Grønt Danmark (Green Tripartite Agreement)*. Retrieved January 8, 2025, from <https://www.regeringen.dk/nyheder/2024/regeringen-og-parterne-i-groen-trepart-indgaar-historisk-aftale-om-et-groent-danmark/>
- Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the Common Agricultural Policy (CAP Strategic Plans) and financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) and repealing Regulations (EU) No 1305/2013 and (EU) No 1307/2013. (2024). Retrieved February 20, 2024, from <http://data.europa.eu/eli/reg/2021/2115/oj>
- Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 (Text with EEA relevance). (29 July 2024). *Official Journal of the European Union*, L 199. Retrieved January 8, 2025, from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991>
- Reidsma, P., Tekelenburg, T., Van den Berg, M., & Alkemade, R. (2006). Impacts of land-use change on biodiversity: An assessment of agricultural biodiversity in the European Union Agricultural land-use change and its drivers in mountain landscapes: A case study in the Pyrenees. *Agriculture, Ecosystems & Environment*, 114(1), 86–102. <https://doi.org/10.1016/j.agee.2005.11.017>

- Rivera-Huerta, A., Rubio Lozano, M. D. L. S., Padilla-Rivera, A., & Güereca, L. P. (2019). Social sustainability assessment in livestock production: A social life cycle assessment approach. *Sustainability*, 11(16), 4419. <https://doi.org/10.3390/su11164419>
- Rivero, M. J., & Lee, M. R. (2022). A perspective on animal welfare of grazing ruminants and its relationship with sustainability. *Animal Production Science*, 62(18), 1739–1748. <https://doi.org/10.1071/AN22208>
- Seidl, R., Müller, J., & Wohlgemuth, T. (2022). Disturbance and biodiversity. In T. Wohlgemuth, In T. Jentsch, A., Seidl, R. (Eds.), *Disturbance ecology* (Vol. 32, pp. 51–66). Springer. https://doi.org/10.1007/978-3-030-98756-5_4
- Shurson, G. C., & Kerr, B. J. (2023). Challenges and opportunities for improving nitrogen utilization efficiency for more sustainable pork production. *Frontiers in Animal Science*, 4. <https://doi.org/10.3389/fanim.2023.1204863>
- Spada, E., De Cianni, R., Di Vita, G., & Mancuso, T. (2024). Balancing freshness and sustainability: Charting a course for meat industry innovation and consumer acceptance. *Foods*, 13(7), 1092. <https://doi.org/10.3390/foods13071092>
- Spiegel, A., Slijper, T., de Mey, Y., Meuwissen, M. P., Poortvliet, P. M., Rommel, J., Hansson, H., Viganì, M., Soriano, B., Wauters, E., Appel, F., Antonioli, F., Gavrilescu, C., Gradziuk, P., Finger, R., & Feindt, P. H. (2021). Resilience capacities as perceived by European farmers. *Agricultural Systems*, 193, 103224. <https://doi.org/10.1016/j.agsy.2021.103224>
- Spigarelli, C., Zuliani, A., Battini, M., Mattiello, S., & Bovolenta, S. (2020). Welfare assessment on pasture: A review on animal-based measures for ruminants. *Animals*, 10(4), 609. <https://doi.org/10.3390/ani10040609>
- Stoddart, A. F. (2013). Climate change and hunger as the challenges in the global food system. *Journal of International Development*, 25(4), 456–472. <https://doi.org/10.1002/jid.3380010208>
- Stranieri, S., Ricci, E. C., Stiletto, A., & Trestini, S. (2022). How about choosing environmentally friendly beef? exploring purchase intentions among Italian consumers. *Renewable Agriculture and Food Systems*, 38, e2. <https://doi.org/10.1017/S1742170522000357>
- Sulewski, P., Kłoczko-Gajewska, A., & Sroka, W. (2018). Relations between agri-environmental, economic and social dimensions of farms' sustainability. *Sustainability*, 10(12), 4629. <https://doi.org/10.3390/su10124629>
- Upton, M. (2024). *The role of livestock in economic development and poverty reduction*. Food and Agriculture Organization of the United Nations (FAO). Retrieved February 10, 2024, from <https://www.fao.org/3/bp224e/bp224e.pdf>
- Veltman, K., Rotz, C. A., Chase, L., Cooper, J., Forest, C. E., Ingraham, P. A., Jolliet, O., Izaurralde, R. C., Jones, C. D., Nicholas, R. E., Ruark, M. D., Salas, W., & Thoma, G. (2021). Assessing and reducing the environmental impact of dairy production systems in the northern US in a changing climate. *Agricultural Systems*, 192, 103170. <https://doi.org/10.1016/j.agsy.2021.103170>
- Wani, A. A. (2024). Comprehensive analysis of clustering algorithms: Exploring limitations and innovative solutions. *PeerJ Computer Science*, 10, e2286. <https://doi.org/10.7717/peerj-cs.2286>
- Wickham, H., Chang, W., & Wickham, M. H. (2016). *Package 'ggplot2'. Create elegant data visualisations using the grammar of graphics (Version 2.1)*. Retrieved February 15, 2024, from. <https://cran.r-project.org/web/packages/ggplot2/ggplot2.pdf>
- Yan, X., Ying, Y., Li, K., Zhang, Q., & Wang, K. (2024). A review of mitigation technologies and management strategies for greenhouse gas and air pollutant emissions in livestock production. *Journal of Environmental Management*, 352, 120028. <https://doi.org/10.1016/j.jenvman.2023.120028>
- Zagata, L., & Sutherland, L. A. (2015). Deconstructing the 'young farmer problem in Europe': Towards a research agenda. *Journal of Rural Studies*, 38, 39–51. <https://doi.org/10.1016/j.jrurstud.2014.11.001>
- Zira, S., Rydhmer, L., Ivarsson, E., Hoffmann, R., & Röös, E. (2021). A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden. *Sustainable Production and Consumption*, 28, 21–38. <https://doi.org/10.1016/j.spc.2021.03.028>
- Zucali, M., Lovarelli, D., Celozzi, S., Bacenetti, J., Sandrucci, A., & Bava, L. (2020). Management options to reduce the environmental impact of dairy goat milk production. *Livestock Science*, 231, 103888. <https://doi.org/10.1016/j.livsci.2019.103888>