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Research article

Characterizing beef and sheep farming systems to customize sustainability interventions and policy implementation

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A B S T R A C T

Agricultural systems tend to be characterised by large diversity, therefore, solving socio-economic and environmental problems in agriculture requires targeted and contextualised policies. However, policies often fail to recognize this heterogeneity in their design or implementation. This can result in the use of sector-wide characteristics and, consequently, generic policies that are not tailored to specific farming systems. In this context, farm typologies can be a useful tool, as they help to identify differences and commonalities in highly heterogeneous groups. In this study, we focused on the Irish beef and sheep farming sectors and used a wide range of structural, socio-economic, and environmental indicators to develop a farm typology. This resulted in the identification of six distinct farm types: Small Cattle Farms, Extensive Sheep Farms, Medium-size Sheep Farms, Medium-size Cattle Farms, Medium-size Mixed Farms, and Intensive Cattle Farms. We then analysed the socio-economic and environmental performance of these six farm types and discussed the potential variation of the implementation and impact of currently proposed policies and interventions among farm types. We argue that failing to consider different farm types within policies can make their farm-level implementation unsuccessful and thus hinder the achievement of sector-wide sustainability goals. The approach we developed in this manuscript could also be applicable to other sectors and locations, and could help guide the design of more successful targeted policies.

1. Introduction

Efficient agricultural policies are key to sustainably meeting the increasing demand for sufficient and nutritious food (Organisation for Economic Co-operation and Development – OECD, 2022). Policies are expected to support agricultural productivity, farmers' incomes, and the stable supply of affordable food (European Commission - EC, 2023a). Simultaneously, there is a growing need for policies to address environmental sustainability issues such as reducing greenhouse gas (GHG) emissions and managing natural resources (OECD, 2022; EC, 2023a). However, standardized views of farming systems can sometimes hinder policy effectiveness (Bartkowski et al., 2022; Benitez-Altuna et al., 2023). Farming systems tend to be widely heterogenous in numerous aspects but are often classified mainly based on size (i.e., small or large-scale farms) and according to their dominant enterprise only, overlooking their diversity in capabilities, circumstances or resources (Benitez-Altuna et al., 2023; Huber et al., 2024). Furthermore, policies often follow sector-wide generic characteristics (Kelly et al., 2018; Guarín et al., 2020), which tend to depict a farm type that either represents a small part of the sector or is even non-existent. The lack of acknowledgement of the heterogeneity of farming systems can lead to policies following "one-size-fits-all" patterns, which renders them unsuitable for most farms. In the European Union, the Common Agricultural Policy (CAP) is the main policy instrument that, while managed nationally according to local priorities, aims at delivering to the ambitions of the European Green Deal of making the EU's economy and environment sustainable (EC, 2023b). However, despite abundant research showing the high heterogeneity of farming systems, both between and within EU member states, the CAP includes few instruments that reflect farm heterogeneity (Bartkowski et al., 2022).

Research has shown that farm typologies can help guide the design of more successful policies (Andersen et al., 2007; Benitez-Altuna et al., 2023; Graskemper et al., 2021). Typologies can be useful when dealing with highly heterogeneous groups, as they can reduce the complexity of a set of elements (Alvarez et al., 2018). By creating smaller, more homogeneous groups, it becomes easier to find commonalities between farms or groups of farms and to identify points of action that could be applied at a group level (Andersen et al., 2007).

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1.1. The Irish beef and sheep sectors

Within the agricultural sector, livestock farming is central in sustainability and policy discussions, due to its relevance in both socio-economic and environmental terms. In Ireland, the beef and sheep sectors (BSS) play a major role in the agri-food sector, as they represent almost three-quarters of Irish farms and about one-third of the country's territory (CSO, 2020). The BSS are key for the country's economy, being a third of the Irish agricultural economic output and are estimated to support roughly 45,000 jobs in the wider economy (Renwick, 2013) and key for the European meat market as they export 85% of their output (Meat Industry Ireland, 2020), mainly to the EU and UK (Bord Bia, 2023). At farm level, the BSS face major socio-economic challenges, such as low profitability and subsidy dependency (O'Donoghue and Hennessy, 2015). Only around 40% of Irish beef and sheep farms would be considered economically viable (Dillon et al., 2022), compared to 85% of Irish dairy farms. Furthermore, while the whole agricultural sector is facing farm succession issues, the situation for the BSS is particularly dire. According to a 2016 study, around a quarter of beef and sheep farms would be considered at risk (i.e., cases in which the farmer is nearing retirement and there is no successor), compared to just 10% of dairy farms (Ryan et al., 2016).

At the same time, beef and sheep farms are linked to key environmental issues that Ireland needs to address, to meet national and EU environmental targets (Environmental Protection Agency - EPA, 2020). These issues include nature and landscape conservation (i.e., conservation of biodiversity and nature areas), climate change (i.e., GHG emissions), air quality (i.e., ammonia (NH_3) emissions), and water quality (i.e., pollution from agriculture by leaching and run-off nutrients and pesticides). The extensively managed grasslands that characterize BSS farms (i.e., natural permanent pastures and rough grazing areas) play a vital role in Irish habitat networks, thereby supporting biodiversity conservation. Meanwhile, as a whole, the Irish BSS are the most significant contributors to Ireland's GHG and NH_3 emissions and hold major influence in Ireland's water bodies due to the vast territory they occupy (Central Statistics Office, 2020).

Overall, the Irish BSS are facing major socio-economic and environmental challenges and the sectors themselves, as well as the Irish government, recognize a need to improve their performance. Hence, a range of interventions are being discussed and developed to stimulate steps towards a more sustainable future. In that regard, the Irish CAP Strategic plan for 2023–2027, which underpins the implementation of the CAP for Ireland during this period, shows high environmental ambition, as well as a desire to protect farm family incomes (Department of Agriculture Foodand the Marine, 2020). The Minister of Agriculture, Food and the Marine also established the Food Vision Beef and Sheep group (FVBSG) to design and advance on the actions for the BSS to align with the wider national Food Vision 2030 strategy and the Climate Action Plan 2021. The Food Vision 2030 Strategy is a ten-year strategy for the Irish agri-food sector that aims to see a 25% reduction in emissions by 2030, and make Ireland "a world leader in Sustainable Food Systems" (Department of Agriculture, Food, and the Marine, 2022). The FVBSG is comprised of an independent Chair and representatives of relevant stakeholders, such as the industry, farms organizations, agencies and members of the Department of Agriculture, Food, and the Marine.

As part of their latest report, the FVBSG delineated several interventions that could help reduce the sector's GHG, while still expressing their commitment to protecting farm economic viability (Food Vision Beef and Sheep Group – FVBSG, 2022). These interventions included improving live weight performance for beef cattle (i.e., higher, and faster live weight gain rates), reducing the use of chemical fertilisers, encouraging the adoption of clover and multispecies swards, increasing organic production and voluntary extensification and diversification schemes. However, they highlighted that further analysis was required for the design of appropriate policy interventions and schemes. They also recognized that the high heterogeneity present in the BSS, in terms of production systems and conditions, makes the implementation of these interventions difficult, as they are not tailored to specific types of systems (Food Vision Beef and Sheep Group – FVBSG, 2022). Similarly, different subsidy schemes and measures proposed by the CAP, often fail to properly address the BSS heterogeneity (Kelly et al., 2018; Dillon et al., 2010; Buckley and Donnellan, 2020).

So far, farm typologies in Ireland have often been solely based on structural farm characteristics (i.e., classifying farms based on size and economic output) (Micha and Heanue, 2015). Micha and Heanue (2015) partially addressed this gap in the knowledge of Irish farm types by developing a typology grouping dairy and cattle farms according to their profitability, environmental efficiency, and social integration. In this study, we argue that the Irish BSS could benefit from a farm typology that helped guide the tailoring of policies and interventions to their various farm types and we further contribute to filling this knowledge gap by combining structural, management, socio-economic and environmental performance indicators (Gaspar et al., 2007; Ripoll-Bosch et al., 2014; Modernel et al., 2018). This integration of indicators is expected to provide a better understanding of how some of the socio-economic and environmental challenges that the BSS are currently facing affect the different farm types and how targeted policies could better support the development of different farm types in the BSS.

Our aim is, therefore, to platform the role of farm typification as a tool for better policy design within the Irish BSS context. Furthermore, we aim at gaining a better understanding of the heterogeneity of the Irish BSS and focused on the interventions proposed by the FVBSG and several CAP schemes, as an example of the type of generic interventions and subsidies often proposed in policy. We also discussed the potential consequences of their implementation by different farm types, as well as the impact on the overall objectives of both Ireland and the EU of supporting socio-economic and environmentally sustainable farming systems.

2. Material and methods

2.1. Dataset

To develop a typology of the Irish BSS we used data from the 2019 Teagasc National Farm Survey (NFS). The NFS uses a random, nationally representative sample of around a thousand farms (of various types) and provides information on farm structure (i.e., farm and herd size), socio-economic characteristics (i.e., labour requirements or gross margins) and environmental performance (i.e., GHG emissions or nutrient balances). We included 381 out of 870 farms available in the dataset in our analysis, using the following three exclusion criteria. First, farms should be beef or sheep farms. Hence, all dairy, tillage, poultry, and pig farms and all farms with any other type of livestock than beef cattle and sheep were removed from the sample ($n = 415$). Second, farms with missing or invalid values for any of the variables that were relevant for our study were removed ($n = 71$). Finally, three research and not-farmer-owned farms were removed, as we focused on regular farmer-operated farms only.

2.2. Variables

When selecting the set of variables through which we would assess the Irish BSS, we considered the indicators available in the NFS, the goal of our study (Alvarez et al., 2014) and indicators that had been used or developed in similar farming systems typology studies. Details and references of those studies can be found in Table S1, in the Supplementary Material. We focused on farm structure, management, environmental and/or economic performance indicators and developed a final set of 47 variables. The final list, including a brief description of the variables and how they were calculated when they were not taken directly from the NFS, can be found in Table S2, in the Supplementary Material.

2.3. Principal component analysis and cluster analysis

To identify explanatory variables and group farms in homogeneous types we performed a principal component and cluster analysis (PCA and CA) in SPSS version 29 (IBM Company, Chicago, IL, USA). The main objective of a PCA is to reduce the number of diagnostic variables to a limited number of formal variables (principal components). We first prepared the dataset for the PCA by assessing the normality of the variables, normalizing them if needed, and removing highly correlated variables and categorical variables with less than five categories. Details of all the steps taken in this process and further details of our approach to the PCA can be found in Box S1, in the Supplementary Material. In the PCA factors were extracted using a Direct-Oblimin rotation and we applied Bartlett's sphericity test and the KMO measure of sampling adequacy to test sampling validity (Modernel et al., 2018). In the end, we obtained nine principal components (PCs) that were assigned a theme based on the variables included in each of them.

We then used the scores of the PCs as variables to perform the CA. We used hierarchical clustering, following Ward's method (Modernel et al., 2018) and conducted an ANOVA test, both to determine if there were significant differences between clusters and to help decide which would be the appropriate number of clusters. When using five or less clusters, at

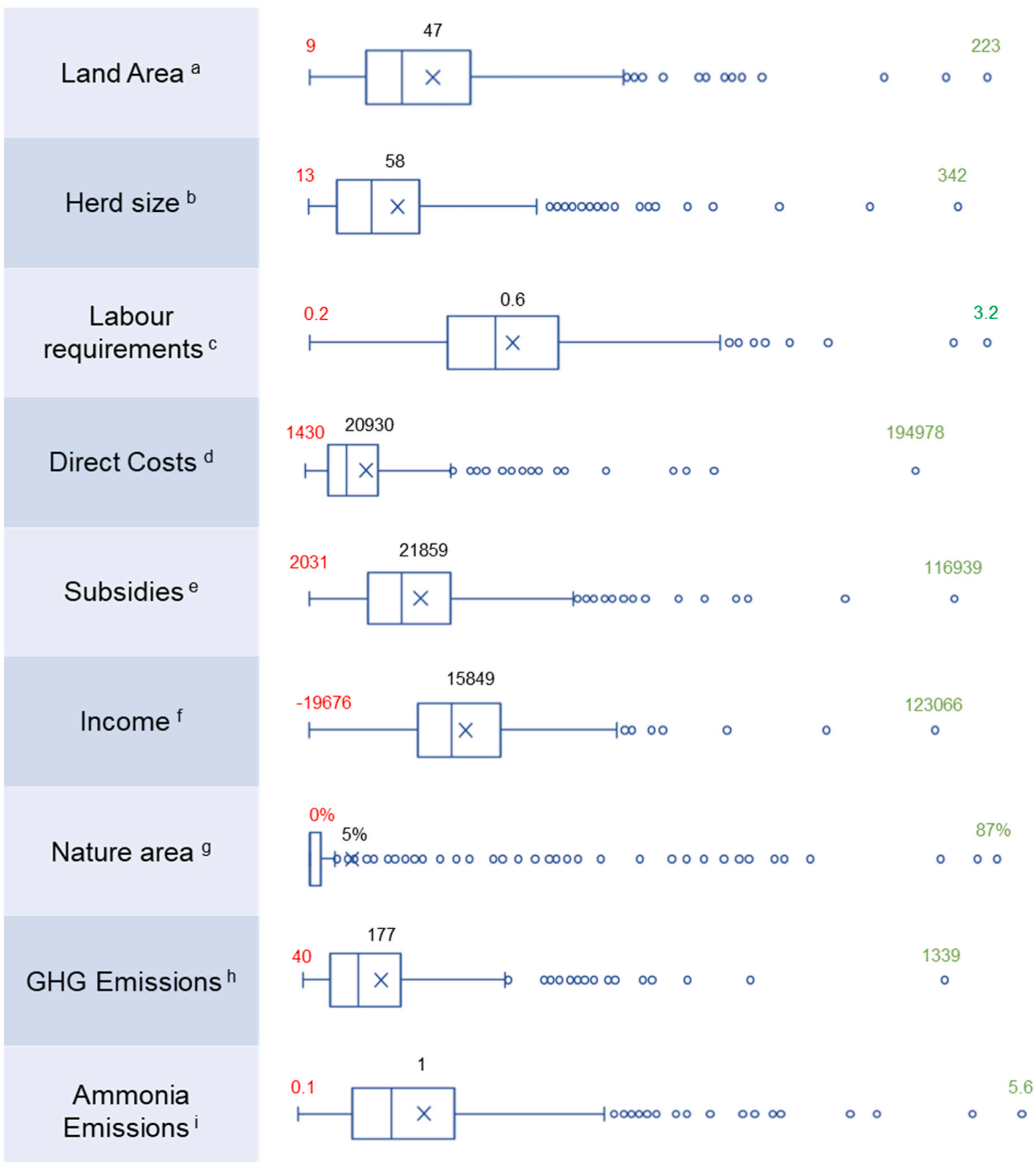

Fig. 1. Distribution of nine farm characteristics across 381 farms from the Irish beef and sheep sectors. The figure consists of boxplots showing the distribution, minimum (in red), maximum (in green), and mean (value above the cross) values. * References: Variables and units: [a] Total Utilized Agricultural Area (ha); [b] Livestock Units (per farm); [c] Labour Units (1 labour unit = 2000 work hours); [d] Direct Costs (€/year); [e] Subsidies (€/year); [f] Income per Labour Unit (€/year); [g] Nature area (%); [h] Greenhouse Gas Emissions (tons of carbon dioxide equivalents per farm per year); [i] Ammonia Emissions (kilograms of ammonia per farm per year). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

least one of the PCs was not statistically significantly different between clusters. Hence, it was decided to use 6 clusters as it was the minimum number of clusters possible that offered a statistically significant difference between components and all variables belonging to the components.

For each of the 6 clusters, representing 6 farm types, we then analysed mean values of the variables in the PCs and performed an ANOVA test and a Tukey's multiple comparison test, to further understand which were the differences between farm types. We also calculated the mean value of the variables in the PCs for the whole sample to better understand our sample and compare its mean to the clusters' means. Additionally, the interpretation of the farm types was supported by expert consultation (Modernel et al., 2018). We presented and discussed the results of our cluster analysis with experts from Teagasc Rural Economy & Development department that work closely with farms in the BSS, NFS data and industry stakeholders from the BSS.

Finally, we discussed the suitability of the interventions proposed by the FVBSG and several CAP schemes to be implemented by the different farm types and the potential impact this implementation may have in terms of achieving the sectors' sustainability goals.

3. Results

3.1. The dataset

Fig. 1 provides a brief overview of some farm characteristics, showing their distribution, minimum, maximum, and mean values in the whole sample. Of the 381 farms, almost three-quarters were classified as part-time farms. The majority of the farms (79%) were classified as either Cattle Rearing or Cattle Finishing farms. All farms classified as Sheep Farms had at least some cattle units. Mixed farms (i.e., farms having both sheep and cattle units) represented 37.5% of the sample. In terms of economic performance, just 31% of the farms would be considered economically viable (i.e., having an Income per labour unit above €20129 – Teagasc, 2021). Regarding generational renewal, most of the farms (63%) scored between 0 and 1, on a scale from 0 to 4 for the Farm Continuity variable. These scores indicate a farmer over the age of 56 or 65, either with a possible successor (score 1) or not (score 0). In terms of training, around half of the farmers in the sample did not have any type of formal agricultural training.

As for the environmental aspects, BSS farms emitted on average 177 CO_2 equivalents (further referred to as eq.) per year, or 10.6 and 13 CO_2 eq. per kilogram of beef and lamb, respectively. Total NH_3 emissions were, on average, 1 kg per farm per year, or 0.06 kg per kg of beef and 0.05 per kg of lamb.

3.2. PCA

The 9 PCs explained 79% of the variance. Details of factor loadings and the percentage of variance explained by each of them can be found in Table S3 in the Supplementary Material. The theme of each PC and the variables that belong to them can be found in Table 1. From the PCs, we can derive that, the scale of the farms is the leading factor contributing to the difference between clusters, as PC1 explains over a quarter of the variance. This scale is however not only reflected in terms of farm or herd size, but also of impact or environmental footprint (GHG and NH_3 emissions) and capital (in terms of subsidies, direct costs, and investments). PC2 consists of three phosphorus-related variables. PC3 is related to the use of feed (other than the on-farm grass resources) as well as emissions efficiency, meaning the emissions per kg of product. PC4 reflects the level of fertilisation and intensity, in terms of stocking rate. PC5 reflects the economic performance, both in absolute terms (i.e., per farm) and relative terms (i.e., per hectare or per labour unit). PC6 is related to the capacity of the families to provide all the labour needed by the farm as well as their ownership over their farmlands. PC7 indicates the type of system, both in terms of the type of animals present as well as whether the farm focuses on rearing or finishing animals. PC8 reflects the social situation of the farmer and, finally, PC9 denotes the type of landscape found on the farm.

Means and standard deviations of the whole sample for all variables in the nine PCs are in Table 1, whereas their overall distribution is showcased in Fig. S1, in the Supplementary Material.

3.3. CA

The hierarchical clustering classified the 381 farms in our sample into 6 clusters (i.e., farm types). We organized the farm types from 1 to 6 in a way that they fitted into a spectrum, going from mainly smaller and/or less intensive farms to larger and/or more intensive farms. Table 1 shows the means and standard deviation values for all the variables included in the 9 PCs for each of the 6 farm types. PC scores for the six farm types can be found in Table S4, in the Supplementary Material.

The farm types can be described as follows:

1) *Small Cattle Farms*: this cluster consisted mainly of small, part-time, cattle-rearing farms. It was the second-largest cluster, representing 19% of the farms in the sample. This cluster scored low for the *Scale*, *Feed and Efficiency*, *Nitrogen Use and Intensity*, *Economic Performance*, *Autonomy* and *Mixed Production and Sales* components, and high for the *Social Vulnerability* component.

In terms of socio-economic aspects, this cluster had the lowest profitability out of the 6 and received the lowest amount of subsidies per farm. As a whole, it represented just 12% of the subsidy expense of the sample. Over 90% of the farms in this cluster had negative market returns and just 17% would be considered economically viable. Farm continuity was low, with 63% of the farms having scores of 0 or 1 in this variable.

In terms of environmental aspects, this cluster's farms had an overall low impact, but low efficiency as well, as they had the lowest mean for GHG and NH_3 Emissions but the highest one for GHG or NH_3 per kg of beef.

2) *Extensive Sheep Farms*: this cluster consisted mainly of part-time, sheep farms. These farms scored low for the *Nitrogen and Intensity* and *Economic performance* components and high for *Social Vulnerability* and *Natural landscape* components. This indicates that they were mainly extensive farms with poor economic performance and large nature areas. They represented just 5% of the farms and raised 4.1% of the LU in the sample, while occupying 8.6% of the land.

In terms of socio-economic aspects, farms in this cluster had mainly negative market returns and almost 80% of them would be considered economically non-viable. They received the lowest quantity of subsidies per hectare and represented only 5% of the total subsidy expense of the sample. This cluster had the highest proportion of farms with scores of 0 or 1 in the Farm Continuity variable.

In terms of environmental aspects, this cluster had the highest percentage of Nature area per farm and, as a whole, managed 62% of the nature area in the sample. In terms of climate and air quality, this cluster was responsible for just 3% of total GHG and NH_3 emissions, being the lowest contributing cluster.

3) *Medium-size Sheep Farms*: this cluster consisted mainly of medium-sized, part-time farms. These farms tended to have a high proportion of sheep, as shown by a high value in the Sheep-to-Cattle Ratio variable, even if the system itself was not classified as a sheep farm. This cluster scored low in the *Economic performance* and *Natural landscape* components, but high in the *Autonomy* and *Mixed production and Sales* components. This indicates poor economic performance and a low proportion of nature areas on the farms. It had the lowest proportion of family labour, and it was the only cluster with

Table 1

Mean (M) and standard deviation (SD) values of the variables belonging to all nine principal components (PC) for each of the six clusters and the average of the whole sample (AV). Different superscript letters (a-e) indicate significant differences between farm types (Tukey test, $p < 0.05$). For all variables with the same letter, the difference between the means is not statistically significant. * SCF: Small Cattle Farms; ESF: Extensive Sheep Farms; MSF: Medium Sheep Farms; MCF: Medium Cattle Farms; MMF: Medium Mixed Farms; ICF: Intensive Cattle Farms. ** A value higher than 100% indicates farmers owned extra land that was not used for their beef and sheep farming enterprise.

PC: Theme/Variable	Units	Stat.	AV	Clusters: Number of farms and % of the sample they represent*					
				Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
				SCF	ESF	MSF	MCF	MMF	ICF
				71 (19%)	19 (5%)	32 (8%)	65 (17%)	167 (44%)	27 (7%)
PC1: Scale									
Greenhouse gas emissions	CO_2 eq.	M	177	103^{a}	140^{ab}	164^{ab}	164^{b}	160^{b}	547^{c}
		SD	146	57	76	104	79	110	180
Ammonia emissions	kg of NH_3	M	0.99	0.6^{a}	0.8^{ab}	0.9^{ab}	0.9^{b}	0.9^{b}	3.0^{c}
		SD	0.8	0.4	0.5	0.6	0.4	0.6	0.9
Livestock units	LU/farm	M	58	33^{a}	48^{b}	58^{b}	50^{ab}	55^{b}	171^{c}
		SD	47	18	25	46	23	38	50
Total utilized agricultural area	ha	M	47	35^{a}	81^{b}	41^{ab}	37^{ab}	47^{ab}	96^{b}
		SD	32	18	56	23	19	28	36
Subsidies	€	M	21859	14165^{a}	23408^{b}	20186^{ab}	19335^{ab}	21896^{ab}	48839^{c}
		SD	14518	8911	11128	14503	9531	11997	21191
Labour requirements	Lab. U.	M	0.63	0.37^{a}	0.54^{ab}	0.58^{ab}	0.54^{ab}	0.62^{b}	1.77^{c}
		SD	0.54	0.21	0.28	0.49	0.31	0.48	0.74
Direct costs	€	M	20844	9682^{a}	18780^{ab}	20611^{b}	20633^{b}	18586^{b}	66403^{c}
		SD	20930	4873	9000	12644	9621	19053	31853
Investments	€	M	61811	36756^{a}	40456^{ab}	74870^{b}	58605^{ab}	52536^{ab}	192337^{c}
		SD	63493	29495	22611	65054	47447	41927	117838
PC2: Phosphorus									
Phosphorus balance	kg/ha	M	5.6	4.8^{abd}	5.7^{abd}	3.8^{ab}	12.3^{cd}	3.2^{ab}	9.2^{acd}
		SD	7.9	3.8	4.1	5.4	13.3	5.6	6.1
Phosphorus use efficiency	–	M	70.9	45.2^{acd}	31.7^{acd}	81.8^{ace}	39.4^{a}	99.0^{bcde}	55.4^{acd}
		SD	71.5	23.3	10.7	56.2	19.1	94.8	17.1
Phosphorus application rate	kg/ha	M	7.7	6^{a}	12^{b}	6^{a}	12^{b}	6^{a}	12^{b}
		SD	6.4	4	7	5	7	6	7
PC3: Feed and efficiency									
Feed costs	€/LU	M	131	91^{a}	174^{b}	142^{ab}	163^{b}	126^{ab}	147^{ab}
		SD	109	75	61	75	107	128	94
Livestock costs	€/LU	M	353	302^{ab}	402^{abc}	382^{abc}	438^{bc}	328^{ab}	371^{ab}
		SD	146	97	96	117	137	166	100
Feed	kg/LU	M	427	280^{a}	545^{abc}	453^{abc}	564^{bc}	413^{ac}	468^{ac}
		SD	420	237	234	259	504	481	312
Beef ammonia efficiency	$kgNH_3$/kg of beef	M	0.06	0.09^{a}	0.07^{b}	0.06^{b}	0.06^{b}	0.06^{b}	0.06^{b}
		SD	0.03	0.04	0.02	0.03	0.02	0.02	0.01
Beef emissions efficiency	CO_2 eq./kg of beef	M	10.6	14.7^{a}	10.8^{b}	10.0^{b}	9.8^{b}	9.4^{b}	9.9^{b}
		SD	4.2	6.6	1.7	3.3	2.4	2.9	1.6
PC4: Nitrogen use and Intensity									
Nitrogen application rate	kg/ha	M	59	43^{a}	67^{abc}	57^{a}	86^{bcd}	48^{a}	103^{cd}
		SD	39	24	36	31	44	32	42
Nitrogen balance	kg/ha	M	58	43^{a}	35^{a}	58^{a}	98^{b}	45^{a}	103^{b}
		SD	51	23	24	28	86	32	42
Livestock Intensity	LU/ha	M	1.3	1.1^{a}	0.7^{a}	1.4^{b}	1.5^{b}	1.3^{b}	2.0^{c}
		SD	0.5	0.4	0.4	0.5	0.5	0.5	0.4
Nitrogen use efficiency	–	M	24	16.9^{a}	17.3^{a}	27.7^{bc}	16.2^{a}	30.8^{bc}	21.6^{ab}
		SD	13.6	7.2	6.8	15.7	7.3	14.6	9.5
PC5: Economic performance									
Profitability	€/ha	M	341	158^{a}	171^{ab}	208^{ab}	268^{ab}	484^{c}	384^{bc}
		SD	308	258	162	170	324	301	193
Market return	€	M	−5554	-7361^{a}	-9867^{a}	-11744^{a}	-9003^{a}	-798^{b}	-11553^{a}
		SD	11940	6120	7757	13818	8914	12366	16109
Income per labour unit	€/lab. u.	M	15849	7754^{a}	12154^{ab}	7056^{a}	10985^{a}	21341^{bc}	27902^{c}
		SD	15852	11063	12280	7198	12169	16745	18286
Livestock Productivity	€/ha	M	391	170^{a}	106^{a}	327^{b}	391^{bcd}	496^{cde}	602^{de}
		SD	294	155	109	218	290	296	223
PC6: Labour and land autonomy									
Family labour	%	M	97%	$100\%^{a}$	$98\%^{ab}$	$81\%^{c}$	$100\%^{a}$	$100\%^{a}$	$94\%^{b}$
		SD	1%	0%	5%	20%	1%	1%	14%
Labour costs	€	M	618	18^{a}	396^{a}	4210^{b}	40^{a}	66^{a}	2897^{b}
		SD	2851	83	796	6400	167	251	6632
Owned land	% ha	M	88%	$88\%^{a}$	$86\%^{a}$	$106\%^{b}$**	$84\%^{a}$	$89\%^{a}$	$80\%^{a}$
		SD	24%	20%	29%	37%	23%	21%	24%
PC7: Mixed production and sales									
Sheep to Cattle ratio	LU	M	0.41	0.06^{ac}	1.04^{b}	0.98^{b}	0.09^{ac}	0.54^{bc}	0.21^{abc}
		SD	1.19	0.21	1.60	2.11	0.22	1.36	0.30
Livestock sales	N°	M	84	24^{a}	71^{abcd}	109^{bcd}	53^{ac}	99^{bcd}	210^{e}
		SD	103	21	73	147	44	107	124

(*continued on next page*)

Table 1 (*continued*)

PC: Theme/Variable	Units	Stat.	AV	Clusters: Number of farms and % of the sample they represent*					
				Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
				SCF	ESF	MSF	MCF	MMF	ICF
				71 (19%)	19 (5%)	32 (8%)	65 (17%)	167 (44%)	27 (7%)
PC8: Social vulnerability									
Farm Continuity	–	M	1.3	1.2[abc]	0.9[abc]	1.0[ab]	1.4[abc]	1.3[abc]	1.9[ac]
		SD	1.14	1.1	1.0	1.1	1.1	1.1	1.4
Farmers Training	–	M	2	1.2[ab]	1.2[abcd]	2.3[abcd]	2.6[bcd]	2.0[abcd]	2.8[bcd]
		SD	2.3	2.1	2.0	2.2	2.4	2.3	2.1
PC9: Natural landscape									
Pasture area	% ha	M	87%	89%[a]	42%[b]	94%[a]	91%[a]	89%[a]	89%[a]
		SD	16%	13%	19%	7%	12%	12%	12%
Nature area	% ha	M	5%	4%[a]	53%[b]	1%[a]	2%[a]	3%[a]	5%[a]
		SD	14%	8%	21%	4%	8%	8%	10%

extra owned land (i.e., farmers owned land that they were not farming, either at all or themselves)

In terms of socio-economic aspects, this cluster was the furthest from achieving a positive market return out of the 6 clusters, followed closely by the Intensive Cattle Farms cluster. This cluster had the largest proportion of non-viable farms (91%) and the lowest mean for the variable Income per labour unit.

4) *Medium-size Cattle Farms*: this cluster consisted mainly of medium-size cattle farms. They were a mix of cattle rearing and cattle finishing farms, most of them with low or no presence of sheep. This cluster scored relatively high for the *Feed and Efficiency* and *Nitrogen use and Intensity* components, which indicates that these farms relied more on external feed, had high use of fertilisers and high livestock intensity.

Both in terms of socio-economic and environmental aspects, this cluster had mid-chart values for most indicators. However, it did receive the highest quantity of subsidies per hectare and represented 15% of the subsidy expense.

5) *Medium-size Mixed Farms*: Representing almost 44% of the farms, this was the largest cluster. This cluster scored the highest in the *Economic Performance* and *Mixed production and Sales* components. It consisted of a balanced mix of cattle rearing, cattle finishing, and sheep farms and the Sheep-to-Cattle Ratio was also balanced. Half of its farms were mixed farms.

In terms of socio-economic aspects, this cluster had the highest profitability, and it was the only cluster that was less than €1000 away from a positive market return, with over 45% of its farms having positive market returns. Mainly due to its size, it was the largest responsible for subsidy expenses, at 44%. Together with the Intensive Cattle Farms cluster, they were the only two clusters with a mean Income per labour unit above the viability threshold, despite still having a high proportion (58%) of non-viable farms.

In terms of environmental aspects, this cluster had the lowest NH_3 and GHG emissions per kg of beef. Despite this and the total emissions per farm being relatively low, it was the largest contributing cluster to both NH_3 and GHG emissions (40%), mainly due to its size, despite not having the largest NH_3 and GHG emissions per farm.

6) *Intensive Cattle Farms*: This cluster consisted mainly of full-time, cattle finishing farms. This cluster scored the highest for the *Scale* and *Nitrogen use and Intensity* components, while having the lowest *Social Vulnerability* score. They held 20% of the LU and occupied 14% of the land, making it the most intensive cluster. Unlike all other clusters, which consisted mainly of part-time farms, 96% of its farms were full-time farms.

In terms of socio-economic aspects, this cluster had the highest mean for the Subsidies variable, with the second-highest value for this variable (that of the Extensive Sheep Farms cluster) being less than half of this cluster's value. However, it only accounted for 16% of the subsidy expenses. It had the second lowest market returns, but it was the only cluster with more than half of its farm (66%) above the viability threshold. It had the highest proportion of farms with scores of 3 and 4 for the Farm Continuity variable, which means farmers were between 40 and 55 years old, with a possible successor (3) or younger than 40, with (4) or without (3) a possible successor.

In terms of environmental aspects, this cluster had the highest mean for total NH_3 and GHG emissions and represented 22% of the total NH_3 and GHG emissions of the sample, despite being just 7% of the farms.

4. Discussion

4.1. Dataset and methodology

In this study, we were able to identify six distinct farm types reflecting the heterogeneity within the Irish BSS. We were able to gain a better understanding of the BSS and their socio-economic and environmental performance. Our farm types were recognized by local specialists dealing with farms from these sectors, as well as with the National Farm Survey.

Our PCA resulted in nine PCs, with a total of 33 explanatory variables, which is a larger number of components compared to other farm classification studies, which normally obtain between three and six components (Gaspar et al., 2007; Ripoll-Bosch et al., 2014; Micha and Heanue, 2015; Modernel et al., 2018). In terms of farm types, most studies identified four. The large number of PC and farm types in our study not only reveals the high heterogeneity of the Irish BSS, but also highlights the many drivers that explain it. Although scale (i.e., farm and herd size), as found by the percentage of variance explained by PC1, does play a key role in farm classification (Finneran and Crosson, 2013), our results also show the importance of considering many other factors when trying to understand farm variability in terms of both socio-economic and environmental performance. One surprising result when analysing our results was the phosphorus-related variables in PC2. Previous studies have identified phosphorus-related variables as proxies for soil quality and the use of advisory services (Buckley et al., 2016) in dairy farms and for soil type (i.e., organic, or mineral) in grasslands (Gonzalez, 2019). However, in our analysis, we were not able to find a strong correlation between the variables belonging to this component and the soil or advisory-related variables in our original dataset. Previous research highlights that phosphorus use and balance largely depend on the type of production (Buckley et al., 2016). Hence, we would suggest further research to clarify the meaning of this component and the use of phosphorus in the context of the Irish BSS.

By exploring a large number of indicators and both cattle and sheep systems together we were also able to expand on previous typologies. The typology by Micha and Heanue (2015), for instance, found that their cluster distinction was not as clear for the cattle farms as it was for the dairy farms in their study. They attributed that to cattle farms often being mixed with other farming activities, which may have had an effect on performance variability. The NFS classifies farms as either Cattle or Sheep farms, based on their main economic activity. This can mask variations in mixed farms (Barnes et al., 2022) that, as suggested by Micha and Heanue (2015), can have an impact on farm performance. By including cattle and sheep farms alike in our study, we were able to solve this issue as we focused on their performance as a whole and not just on the main economic activity that would drive their classification in the NFS. We were able to reveal that, despite being classified as Sheep Farms in the NFS, all farms had at least some cattle livestock units. Furthermore, many farms classified as either Cattle Finishing or Cattle Rearing also had sheep livestock units, which indeed influenced their economic and environmental performance. Although excluding farms that had other types of livestock from our sample hindered our result's capacity to capture more diverse farms, by including both cattle and sheep farms together we were able to gain a better understanding of the ruminant meat sector.

4.2. Performance of the different farm types

Although the profitability of the BSS sectors was generally low, we observed clear variance between farm types in terms of socio-economic performance. Less intensive or smaller farms, like those in the Small Cattle Farms and Extensive Sheep Farms clusters, were clearly outperformed by the more intensive or larger farms in the Medium Mixed Farms and Intensive Cattle Farms clusters in economic terms. However, profitability was higher in the Medium Mixed Farms cluster than in the Intensive Cattle Farms cluster, which could be showing that the role of scale and intensity in good socio-economic performance, although important, was somewhat limited (Ripoll-Bosch et al., 2014). All clusters had negative Market Return means, which indicates that none of the farm types could cover their operation costs or make any profit without subsidies. A similar trend has been observed in studies on ruminants in other countries (Belanche et al., 2021; Ripoll-Bosch et al., 2014; Bernués et al., 2011). However, it is worth noting that the smaller and less intensive farms were not the main drivers of the total subsidy expense, despite their high dependence on subsidies at farm level. The low viability of the sector can also be seen throughout the farm types, but again the role of scale and intensity is noted, for instance by the fact that the Intensive Cattle Farms cluster had the highest proportion of viable farms. Despite their low profitability and almost three-quarters of the farms being part-time farms, a majority of the farmers indicated not having another source of employment. However, we did not have data on other potential income sources, such as other family members being employed outside of the farm or income from rents and investments. Off-farm income have been described as a threat and as an opportunity to farm long-term viability (Muñoz-Ulecia et al., 2021). Hence, further information on that regard could provide insights into farm dependence on complementary incomes. As for the social aspect, a general risk in the agricultural sector is the lack of generational renewal (EC, 2018; Ryan et al., 2016; Terres et al., 2015). Although all farm types were affected and the sample showed low values for the variable Farm Continuity throughout, sheep farms appeared to be at higher risk. The two farm types with a large proportion of sheep (i.e., Extensive Sheep Farms and Medium Sheep farms) had the lowest farm continuity. This finding aligns with findings from other European countries (Belanche et al., 2021; Bernués et al., 2011) as well as from the Irish Farmer's Association (IFA) views, who considers that the general disadvantageous conditions of sheep farming make it very hard for new farmers to take on sheep enterprises (The Irish Farmer's Association, 2023).

Environmental performance also varied greatly between farm types. Variability of environmental impacts across farms and farming systems has been described before, particularly for ruminants and for the impacts on e.g., biodiversity (Kok et al., 2020), greenhouse gas emissions (De Vries and De Boer, 2010) or other environmental aspects (de Vries and de Boer, 2010). In our study, when considering the issue of the conservation of nature areas, we saw that although 5 farm types had between 1 and 5% of their area dedicated to nature, the Extensive Sheep Farms cluster had over 50%. This means that this farm type has a large potential for impacting nature and biodiversity either negatively (if they are not properly managed) or positively (when proper practices and conservation measures are adopted). It is important to notice that this indicator, did not provide insight into which specific ecosystems were included, their quality or their capacity to support biodiversity. Hence, further research would be needed to assess this. When analysing the performance regarding climate change (i.e., GHG emissions), we believe it is important to consider both total GHG emissions and intensities (i.e., GHG/kg of product), as a measure of efficiency (Gerber et al., 2013). For instance, if we focus on the emission intensities of our farm types, we see that the Small Cattle Farms cluster had significantly higher emissions per kg of beef than all the other farm types. However, they had the lowest total GHG emissions per farm. Meanwhile, the Intensive Cattle Farms cluster, had lower emissions intensities but its emissions per farm were over three times higher than the average of the whole sample. Hence, depending on the GHG metric considered, either of these two could be deemed as the worst-performing farm type, which would be a misleading conclusion. Understanding the metrics is key to designing interventions to reduce GHG emissions and to avoiding unintended effects (Segovia-Martin et al., 2023). While the reduction in emission intensities is important, the main ultimate goal should be an absolute reduction in GHG. In the case of NH_3 emissions, which is one of the five main pollutants affecting air quality in Ireland (EPA, 2020), although the trends in our results are similar to GHG emissions, different considerations need to be taken into account. With GHG emissions, due to their global effect, a total reduction of overall emissions is a key goal. For NH_3 emissions, however, local impact is more relevant (i.e., emissions per unit of area). Interventions that would reduce overall emissions of the sector or increase efficiency need to also provide a reduction of emissions in each farm and local area (Jacobsen et al., 2019). Finally, in terms of the risk posed for water pollution, nitrogen and phosphorus balances can be used as indicators of nutrient surplus potential, which reflects the risk of nutrient losses to water bodies (Buckley and Donnellan, 2020). The Medium Cattle Farms and the Intensive Cattle Farms clusters had significantly higher nutrient balances than the other four clusters, which indicate a higher risk for water pollution. The Medium Mixed Farms cluster in turn, had the lowest phosphorus balance and one of the lowest nitrogen balances. This is worth noting since it is the cluster holding most of the land and could, hence, also be the cluster affecting most water bodies.

It is important to highlight, however, that the farm types identified in this analysis are not fixed (Benitez-Altuna et al., 2023). The data used, as well as the indicators selected in our study, show a snapshot of Irish BSS farms and either selecting data from different years or focusing on different indicators could result in farms shifting from one cluster to another or cluster numbers or characteristics to change (Benitez-Altuna et al., 2023).

4.3. Considering heterogeneity to customize sustainability interventions and policy implementation

Acknowledging the heterogeneity in farming systems is extremely important when designing policies and interventions (Bartkowski et al., 2022; Benitez-Altuna et al., 2023). Although working with generic measures and averages provides easy and attainable data, and facilitates communication, there is no such thing as an "average farm" that serves to design blueprint interventions. In Ireland, policies and interventions proposed by the CAP Strategic Plan for 2023–2027 or the FVBSG, for instance, to our understanding, do not fully consider farm heterogeneity within the BSS. Hence, they may fall short in the goals of supporting socio-economic and environmentally sustainable farms.

Some of the measures delineated by the FVBSG include a) improving live weight performance resulting in earlier slaughter ages b) reducing chemical N use by 27%–30% by 2030; c) increasing the area under organic production; d) encouraging clover and multispecies swards adoption and ensure all farmers have incorporated clover/multispecies on 20% of their farm grassland by end of 2025 and voluntary e) diversification (i.e., voluntary removal or reduction of herd sizes and the development of other nonbreeding beef or sheep enterprises and/or other farm enterprises) and f) extensification schemes (i.e., voluntary reduction of herd sizes). Some of these measures are also reflected in the CAP Strategic Plan 2023–2027 subsidy schemes, such as the Suckler Carbon Efficiency or the Organic Farming Scheme. However, it is unclear whether all farms should implement those measures, and if not, who should apply what to ultimately achieve the goals for the sector. Examples from other countries have already confirmed that when dealing with highly heterogenous farming sectors, policies and interventions cannot be equally implemented by all farm types (Graskemper et al., 2021; Bartkowski et al., 2022; Stetter et al., 2022; Benitez-Altuna et al., 2023). Different farm types will face different challenges when adopting interventions and the potential benefits gained from adopting interventions will differ depending on the farm types that implement them.

For example, in the Irish BSS case, the inclusion of clover or multispecies swards in the farms (measure "d" above) is considered to increase biodiversity, increase forage and animal productivity, while decreasing the need for external inputs and the emissions of greenhouse gases (Baker et al., 2023). Meantime, this measure is also associated with higher initial production costs (i.e., from re-seeding) (Schaub et al., 2021) and knowledge or labour requirements (i.e., for the management of the new swards) (DLF, 2021). While this option sounds very promising, it has different implications for different farming systems. For instance, the Small Cattle Farms or Extensive Sheep Farms clusters could face difficulties, as both farm types have very limited investment capacity and consist mainly of part-time farms. Due to their low intensity, it is also possible that these two farm types might be underutilising their existing grass resources, and may hence benefit first from an improved grassland management (i.e., rotational grazing) than from reseeding, which would require lower inputs and have lower investment costs. Furthermore, both interventions (i.e., reseeding, or improved grassland management) could also aid in improving live weight performance (measure "a" above). However, the increased labour requirements of both interventions may also render them unsuitable for these part-time farms. Moreover, for the Extensive Sheep Farms cluster, it would be debatable whether the conversion of 20% of their grassland area to clover or multispecies would actually be beneficial, both in terms of environmental and economic performance. Justifying the intervention for the sake of reducing GHG emissions would be debatable since this farm type was only responsible for 3% of the total GHG emissions of the sample and the total abatement capacity would be limited. Meantime, reseeding could result in detrimental effects on the vast natural landscapes that the farms in this farm type manage, releasing soil organic carbon (Reinsch et al., 2018) and negatively affecting biodiversity and landscape conservation. For the Small Cattle Farms cluster, the inclusion of clover or multispecies swards could increase their efficiency in terms of GHG emissions per kg of beef, which was the lowest out of the six farm types, as well as their live weight gains (Grace et al., 2019). Hence, despite the difficulty for this farm type to implement this measure, the benefit might be large for the sector as a whole, because it is the second largest cluster (19% of farms). Farms in the last two clusters (Mixed Medium Farms and Intensive Cattle Farms) could potentially afford the investment associated with the inclusion of clover or multispecies swards. The Intensive Cattle Farms cluster, as a cattle finishing farm type, could particularly benefit from the higher grass availability associated with multispecies swards (Baker et al., 2023), which could be translated into higher live weight gains. Furthermore, any reduction in the GHG emissions from these two clusters would have a major effect on the overall emissions of the BSS, as they are the largest contributors in the sample. Therefore, incorporating clover and multispecies swards in 20% of the grasslands of all farms might not be the best strategy. Instead, it may be more beneficial that farms from the Intensive Cattle Farms cluster aim at incorporating larger proportions of clover and multispecies swards, whereas farms from the Extensive Sheep Farms cluster do not incorporate them at all (depending on the condition of the current established permanent grassland).

It is worth noting that some of the measures pose an even greater challenge when trying to understand which farm types would be able to implement them, and the benefits their implementation might bring. In the case of chemical N reduction, for instance, the FVBSG highlighted two key challenges. First, the diversity of the systems and then, the fact that extensive farms that were already applying it at very low levels would find it challenging to significantly reduce its application (Food Vision Beef and Sheep Group – FVBSG, 2022). Hence, we could argue that the Extensive Sheep farm cluster may not be a suitable candidate for this measure, while the Medium Cattle Farms and Intensive Cattle Farms clusters, for instance, would have more room for chemical N reduction. However, it could also be argued that farms that are already operating with low N inputs might find it easier to further reduce chemical fertilisers or even consider a switch to organic farming (Escribano, 2016; EC, 2023c), while farms with higher dependency would find it more challenging. In any case, small reductions in farm types with higher use could mean significant overall reductions in the sector. This dichotomy needs to be considered when tailoring the interventions and policies to each farm type.

Similar arguments would hold, for example, for extensification measures. It could be argued that would be most effective for the most intensive farms to reduce their herds. However, this may jeopardise their viability, as they depend on their herd size and intensity to be viable. Hence, it needs to be considered whether it would be more beneficial for the sector as a whole that these intensive farms extensify or if it would be more beneficial to concentrate production in this type of farms and let the extensification and diversification schemes target farm types with already extensive and small farms, so that they continue to be viable, while not further intensifying or abandoning production either. It is worth noting that many stakeholders of the FVBSG argue against extensification and diversification measures, as they believe they pose a risk for land abandonment. However, research has shown that the main risk factors for land abandonment are low incomes and high farmer's age (Terres et al., 2015). Considering both the low profitability and low farm continuity that we found in most farm types, the risk of land abandonment is already a stark reality for the BSS. We could instead argue that farm diversification can potentially help address land abandonment, by addressing income stability and supporting local economies (EU, 2016).

With this discussion, we aim to showcase some of the necessary considerations that should accompany the design of policies, interventions, and subsidy schemes for the Irish beef and sheep sector, in which the sector's heterogeneity is considered (Stetter et al., 2022; Benitez-Altuna et al., 2023). Considering farm heterogeneity when designing policies better aligns with the growing call to adopt policy mixes (Edmondson et al., 2019; Kanger et al., 2020), instead of pursuing main policy instruments to achieve single goals. In other words, whereas the mainstream policy approach has been to focus on finding the 'best' policy instruments with the 'most optimal' results, current advice is to shift to the interaction and mutual support of different instruments aiming to identify their optimal combination (Kanger et al., 2020). Generic interventions fall short when trying to address current sector-level environmental and socio-economic problems. Instead, we should look for different interventions for different farming systems that yield an optimal combination at the sector level.

The methodology and approach developed in this manuscript could also be used in other sectors and/or locations that would benefit from policymakers better understanding their heterogeneity. A proper discussion on which interventions are more suited for which farm types should also be done with participative processes (Bayley and French, 2008) where stakeholders can negotiate and decide about the desired pathway for the different farm types to contribute to the overall socio-economic and environmental goals of their sector. Meantime, we also acknowledge that accounting for heterogeneity in policy design may incur additional costs and difficult their implementation (Huber et al., 2024). Hence, a balanced approach is needed. Furthermore, other factors that exceed the scope of this study need to be considered, such as correct market strategies and consumer demand for certain products, or the willingness and ability of the farmers to accept and implement changes in the production systems (Westerink et al., 2023). Individual differences in attitudes and beliefs may also influence farmer's responsiveness to policies and interventions.

5. Conclusions

We found six unique farm types that reflect the high heterogeneity in the Irish BSS. Although the sector as a whole is facing major socio-economic and environmental challenges, these vary between farm types. As it is a very relevant sector for the Irish economy, several interventions have been put forward to address these challenges. However, stakeholders (i.e., farmers associations, farmers, and industry), including the government, need to consider the heterogeneity of the sector to tailor these interventions and policies to the different farm types. Not all farm types can be expected (nor need) to implement every possible solution or do so in the same way. Some farm types may have more options towards reducing GHG emissions within their current livestock enterprise, others might be able to do it through diversification, while others may be better suited for contributing towards halting biodiversity loss and the maintenance of natural landscapes instead. All in all, tailored interventions would better fit both the different farm typologies and the overall sustainability objectives of the sector.

CRediT authorship contribution statement

M.C. Ayala: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **J.C.J. Groot:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis. **K. Kilcline:** Writing – review & editing, Validation, Supervision, Resources, Data curation, Conceptualization. **C. Grace:** Supervision, Resources, Project administration. **J. Kennedy:** Supervision, Resources, Project administration, Funding acquisition. **B. Moran:** Validation, Resources, Data curation, Conceptualization. **I.J.M. de Boer:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **R. Ripoll-Bosch:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relation-ships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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