Animal 19 (2025) 101566

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

A practical approach to assess the resilience attributes of livestock farms

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ARTICLE INFO

Article history:
Received 18 December 2024
Revised 28 May 2025
Accepted 2 June 2025
Available online 9 June 2025

Keywords:
Goat
Indicators
Methodology
Quantification
Sheep

ABSTRACT

There is a growing interest in studying farm resilience. Typically, resilience assessments focus on crisis outcomes, with less attention paid to assess the system characteristics that contribute to building resilience, i.e. resilience attributes. This is partly due to a lack of practical approaches to assess these attributes. The objective of this paper is to develop a practical approach to assess and compare the status of livestock farms' resilience attributes in different farming systems. We identified 21 resilience attributes that generally contribute to farm resilience based on a literature review. We operationalised resilience attributes into 85 indicators quantifiable through primary farm data, such percentage of feed produced on the farm. We assessed three small ruminant case studies in Spain: (i) meat sheep farms in Aragón; (ii) dairy sheep farms in the Basque Country and Navarre; (iii) dairy goat farms in Andalusia. We conducted farmer surveys (n = 144) to measure the indicators, and organised three workshops with farmers and other local stakeholders (n = 20) to assess the importance of the resilience attributes in the three case studies. We aggregated indicators into resilience attribute scores using a minimum–maximum normalisation procedure. Using stakeholders' assessments, we calculated attribute weights by a budget allocation process. Attribute scores and weights were then used to calculate an overall resilience score (ranging from 0 to 100). The comparison of attribute scores revealed strengths and weaknesses for resilience in each case study. In the meat sheep system, honours legacy was a major strength, while work and quality of life was a weakness. In the dairy sheep system, sector organisation was a major strength, while the redundance of productive alternatives was a weakness. For dairy goat farms, the infrastructure of the areas where farmers live was a major strength, but feed autonomy and the attributes related to the access and use of natural resources were weaknesses. The perceived importance of attributes (weights) differed across cases. Particularly, human capital emerged as one of the most relevant ones across case studies. Farms' overall resilience scores were significantly lower in the dairy goat system. Our approach allows to find what attributes build resilience in farms and to highlight areas of improvement to strengthen their resilience. Our findings are of importance to farmers, technicians and policymakers who are interested in assessing resilience as we provide a practical approach to quantify and compare resilience of farms.

Implications

Resilience attributes are key for building resilient farms, but empirical approaches to assess these attributes in large numbers of farms are lacking. Our work provides a practical approach for assessing farms' resilience attributes in different farming systems. The approach can identify the attributes in which farms of a particular system perform better or worse than others in resilience terms. This approach can be used to assess what farm attributes should be improved before an unexpected crisis happens. This is valuable for farmers, technicians and policymakers who are

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https://doi.org/10.1016/j.animal.2025.101566
1751-7311/

interested in assessing resilience, as we provide a practical approach to quantify and compare resilience of farms in real conditions.

Introduction

In the current global change context, European farms are struggling to cope with a variety of social, economic, political and environmental challenges (Meuwissen et al., 2020), and they need resilience to do so (Darnhofer, 2014). Typically, to understand farm resilience the primary focus is on outcomes after a crisis event: e.g. whether there were supply disruptions to retail during COVID-19 lockdowns (Coopmans et al., 2021; Måren et al., 2022). Limited attention is paid to the characteristics that contribute to building a resilient system (Darnhofer, 2021a), which are called resilience properties (Cabell and Oelofse, 2012) or resilience attributes (Boahen et al., 2023). These include a system's diversity (Dardonville et al., 2020) or the connectedness with other systems (Meuwissen et al., 2019). For example, the European Commission's Farm to Fork Strategy (European Commission, 2020) focuses mainly on improving farms' economic and environmental performance, but does not specifically address resilience attributes (Mathijs and Wauters, 2020). These resilience attributes are expected to improve farms' ability to cope with (un)expected events and help farmers to deal with uncertainty (Meuwissen et al., 2019). However, clear guidelines to empirically measure and assess resilience attributes on farms are still lagging behind (Feindt et al., 2022).

The Resilience Alliance (2010) developed guidelines to assess resilience in socioecological systems and identified five principles that confer resilience: system reserves, diversity, modularity, openness and tightness of feedbacks. These principles were integrated by Meuwissen et al. (2019) into a theoretical framework to assess the resilience of farming systems. Stemming from this framework, Paas et al. (2021a) extended the five resilience principles to a list of thirteen attributes that contribute to resilience of farming systems. They grounded these attributes in earlier work of Cabell and Oelofse (2012), who compiled specific attributes and indicators that contribute to resilience in socio-ecological systems. While these studies consider the role of attributes in enhancing resilience, they do not provide an approach for assessing them in practice. The Food and Agriculture Organization of the United Nations (FAO, 2015) developed a method to assess the resilience to climate change of pastoral farmers' households in developing countries (SHARP, Self-Evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists). While being conceptually promising, application to developing countries implies a focus on the household that may be unfit for assessing farm resilience in the European context. Perrin et al. (2024) developed an alternative methodology to assess attributes in European livestock farms. Although the analysis provided very detailed results, the data collection protocol was based on in-depth observation of farm operations, which is not applicable in large farm samples.

Resilience assessments are based on either objective or subjective approaches (Van Der Lee et al., 2022). Objective approaches often have a quantitative character and are based on indicators that are usually selected by experts and are measured with little or no human judgements, such as gross margin per year or feed sufficiency ratio (Jones, 2018; Van Der Lee et al., 2022). Subjective approaches have a qualitative character and rely on participatory methods, such as workshops or interviews that reflect people's perceptions of their own resilience (Jones, 2018; Van Der Lee et al., 2022). Both approaches have advantages and disadvantages and can also complement each other (Jones, 2018; Quandt and Paderes, 2023). Objective approaches can facilitate comparative analysis at a regional level and provide a more robust quantification of the costs and benefits associated with each type of farm (Cradock-Henry, 2021). On the other hand, subjective approaches place a high value on people's understanding of the system they belong to (Jones and Tanner, 2017; Quandt and Paderes, 2023). When studying farm resilience, subjective assessments complement objective assessments by including people's judgements in different socio-economic contexts (Cleves et al., 2022; Cradock-Henry, 2021; FAO, 2015; Quandt, 2018). Previous European studies have assessed the presence of resilience attributes in different farming systems using subjective approaches (Paas et al., 2021a) or mixed subjective and objective methods (Le Goff et al., 2022; Perrin et al., 2024). Nonetheless, there is a lack of methods to quantify resilience attributes and assess overall resilience, especially at the farm scale (Boahen et al., 2023).

The aim of this paper was to develop an approach that integrates multiple indicators to assess the resilience of farms. This helps to quantify and compare the resilience attributes of farms in different farming systems. The approach is developed and applied to three small ruminant farming systems in Spain. These are facing several social, economic and environmental challenges that they are not being able to cope with, which may imply low resilience. However, these farming systems can play a key role in the delivery of ecosystem services in the Euro-Mediterranean region (Bernués et al., 2014) and the sustainability of global livestock production (Cheng et al., 2022). Therefore, studying their resilience is crucial for implementing informed management strategies that prevent further decline. The contributions of this paper are threefold. First, we operationalise general resilience attributes into a concrete list of indicators that is measurable on the farm level at their most meaningful unit, e.g. annual working units (**AWU**) or the percentage of feed produced on farms. This complements the earlier work of FAO (2015) and Perrin et al. (2024), who assessed resilience attributes using categorised indicators. Second, we use indicators to quantify resilience attributes by calculating scores, which allows us to compare resilience attributes across farms. This enriches the earlier insights from Paas et al. (2021a), who assessed attributes with 1–5 Likert scales. Third, we integrate attributes into an overall resilience score per farm based on primary farm data and expert knowledge that benefits from the complementarity of subjective and objective approaches and enables to compare the resilience of different systems (here farms). An overall score was not developed in FAO (2015) nor in Perrin et al. (2024) and proved much more difficult to construct using qualitative assessments, such as in Meuwissen et al. (2020).

Material and methods

Fig. 1 illustrates the four steps followed to assess the farm resilience: (1) identification of resilience attributes; (2) operationalisation of resilience attributes to their underlying indicators; (3) data collection, which comprises measuring the indicators using farmer surveys and the elicitation of attribute weights in three case studies; (4) calculations to build attribute scores, attribute weights and an overall resilience score.

Case studies

Small ruminant farming systems in Spain are facing many economic (e.g. low farm income or considerable dependence on European Common Agricultural Policy (**CAP**) subsidies) and social (e.g. little generational renewal) challenges (Belanche et al., 2021; Dubeuf et al., 2016). This has led to a decline in the number of small ruminant farms and animals, as evidenced by a reduction in the number of sheep and goats by around 41 and 13% respec-

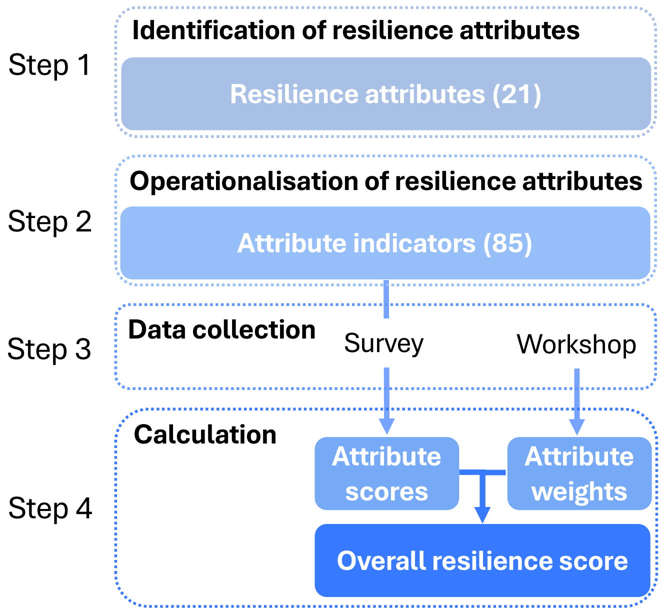

Fig. 1. Graphical representation of the followed steps to assess resilience in small ruminant farms. The numbers in brackets refer to the number of elements considered in a category.

tively since 2000 (MAPA, 2022a). These trends illustrate that the resilience of these farms is very limited and needs to be improved to prevent their collapse (Paas et al., 2021b). Otherwise, farm exits may reduce the economic activity in disadvantaged areas, where farming represents an important social and economic activity. This leads to a loss of ecosystem services, such as forest fire prevention, production of high-quality products and biodiversity conservation (Bernués et al., 2005, 2016; Oteros-Rozas et al., 2014).

The three case studies were purposefully selected as they represent significant agroecosystems and value chains in Spain: (i) meat sheep farms in Aragón; (ii) *Latxa* breed dairy sheep producers of Protected Designation of Origin (**PDO**) '*Idiazabal*' in the Basque Country and Navarre; (iii) dairy goat farms in Andalusia. Fig. 2 depicts the sampled farms.

The sheep meat case is located in northeast Spain. The main product in the meat sheep farming system is lamb, a product

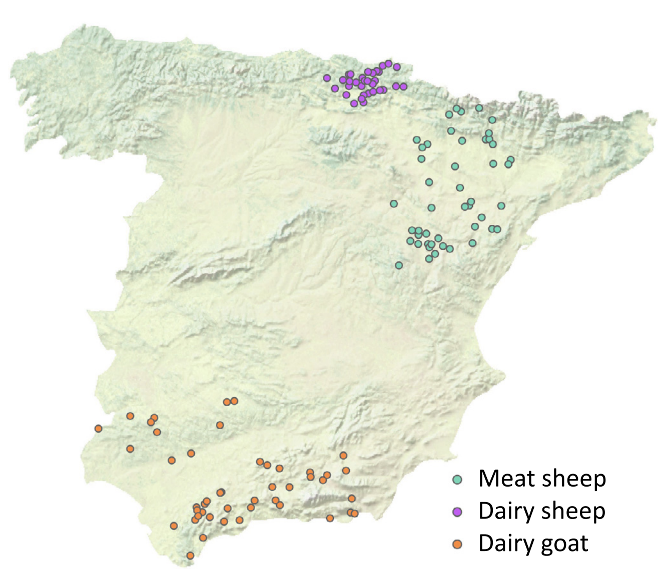

Fig. 2. Location of the small ruminant farms.

marketable according to the Protected Geographical Indication '*Ternasco de Aragón*'. Most flocks include the *Rasa Aragonesa* local breed and sometimes other regional breeds adapted to the environmental conditions. Farms are mixed and closely linked with the territory, usually using feed resources from rainfed or irrigated crops. Ewes normally graze most of the year in fallows and rangelands, depending on the location. Animals are supplemented with concentrates, maize and/or barley, alfalfa and straw (Barrantes et al., 2009), mainly at the end of pregnancy and during lamb rearing. Farms have several lambing seasons per year, making production stable along the year. The average flock size is 910 sheep, and the average number of lambs sold is 1,4 per ewe per year (Pardos et al., 2022).

The dairy sheep farming system investigated (*Latxa* breed) is located in north Spain. Its main product is milk, which is mostly processed into cheese according to the PDO '*Idiazabal*'. The business model involves cheesemakers and dairies. Cheesemakers process the milk from their own sheep, make cheese on-farm and marketed through short channels. Dairies sell the milk to industry. Feed management is based on local resources: valley and/or mountain pastures and on-farm fodders such as grass hay, alfalfa hay and grass silage. Ewes are supplemented with concentrates (mostly based on barley and maize) and legumes (soya, peas, beans, etc.), mainly at the end of pregnancy and during lactation. The system is seasonal, usually based on a single lambing per year. According to the Confederation of Associations of *Latxa* and *Carranzana* Sheep Breeders (CONFELAC), the average flock size is 382 sheep, and the average milk yield is 201 litters per ewe and year (personal communication).

The dairy goat case study is located in southern Spain. The main product is milk, which is usually sold to industry for further processing. The dairy goat breeds are *Murciano-Granadina*, *Florida*, *Malagueña* and *Payoya*. This case study adopts a wide array of feed management practices, ranging from farms relying on natural resources supplemented with some concentrates to farms with no access to land and heavily relying on purchased forages and concentrates (Morales-Jerrett et al., 2022). In farms with large use of natural resources, there is a seasonal production in the first half of the year. In those with no access to land, production is distributed throughout the year. The average flock size is 428 goats, and the average milk yield is 472 litters per goat per year (Morales-Jerrett et al., 2022).

Identification of resilience attributes

We adopt the resilience framework proposed by the Resilience Alliance for socio-ecological systems (2010), which was further tailored to agricultural systems by Meuwissen et al. (2019). This framework considers farm resilience to be a property that is enabled by resilience principles. These principles are system reserves, diversity, modularity, openness and tightness of feedbacks. The resilience principles are essential for farms because they contribute to their ability to be robust, adaptable and transformable when facing challenges (Dardonville et al., 2021).

Based on these principles, more concrete resilience attributes are needed to assess general resilience (Paas et al., 2021a). We developed farm-level attributes for each resilience principle based on Cabell and Oelofse (2012), Paas et al. (2021a) and Darnhofer (2021b), following the procedure described in Prat-Benhamou et al. (2024). Attributes cover farm characteristics that are implicit in each resilience principle. The attributes were identified based on an expert-based iterative process, where attribute definitions and their links with principles were modified by the project team (i.e. researchers and members of producer associations and cooperatives involved in the RUMIRES Project, referenced in the Acknowledgements). We repeated this procedure until a consensus on the conceptual consistency between attributes and principles was reached. This implied aligned definitions between principles and their associated attributes and no overlap in the definition of attributes associated with different principles. More details about the definition of principles and the identification of attributes can be found in Supplementary Material S1. In total, we considered 21 attributes. The reader can consult Supplementary Table S1 for an overview of the resilience principles and attributes.

Operationalisation of resilience attributes into indicators

We operationalised the resilience attributes based on the premise that they can be measured on the farm-level using simple data collection protocols (i.e. one survey per farm, to be completed in 1–2 h). The project team identified indicators that could match each of the 21 resilience attributes, yielding a total of 85 indicators (Table 1). The resilience attributes included in the study are depicted in italics throughout the text.

We identified indicators based on a literature review and the interpretation of the project team. Supplementary Table S2 lists the indicators included in the study and the references supporting their selection when applicable. The criteria for selecting indicators were the measurability on farms through surveys and the potential to build farm resilience attributes, which ultimately contribute to resilience. More details about the selection of indicators can be found in Supplementary Material S1. From an initial list of 107 indicators, some were removed because of 10% missing values or more, poor data quality, or doubtful relationship with resilience attributes. This resulted in a list of 85 indicators that constitute formative measures of the resilience attributes. Formative indicators are based on theoretical soundness, and they can be aggregated into composite indices (Diamantopoulos and Siguaw, 2006). Higher values of indicators imply better performance of the corresponding resilience attribute, i.e. higher resilience. This implies that, for example, "Total number of hectares for forage" makes *Access to natural capital* higher, following the definition of this attribute: "Access to the natural resource base on farm agroecosystem boundaries" (Supplementary Table S1).

Data collection

Attribute indicators

We developed a structured face-to-face farmer survey to measure the indicators. The survey was tested with eight farmers to check the adequacy of its questions and format. Afterwards, it was revised and shortened.

The final questionnaire comprised 12 sections (section numbering included in parentheses): farm and farmer general data (1); labour and family structure (2); herd structure and management (3); information for management purposes (4); land and natural resources use (5); biosecurity (6); products and markets (7); profitability and financial resources (8); associations (9); education and knowledge (10); infrastructure and equipment (11); infrastructures and services in the farm area (12).

Participants were selected using a quota sampling method (Pace, 2021) to cover the variability of the farm types in each case study. The criteria were the use of grazing resources on farms, the geographical location, and the age of the farmer. The farmers willing to participate in the study were facilitated by the associations and cooperatives of the RUMIRES project and/or regional veterinary services. The sample size was 144 farms. A description of farms per case study is included in Table 2.

Farmers were interviewed in a face-to-face setting between June 2022 and February 2023 by project team members, who had received specific training. Completing the survey took between 1 and 2 h.

All indicators, whether being categorical (dummy or ordinal) or numerical (continuous or discrete), were numerically coded. Supplementary Table S3 contains the original variable types of the questionnaire, how indicators were calculated, and descriptive statistics per case study.

Attribute weights in each case study

Three participatory workshops were organised to assess the importance (weights) of attributes for building farm resilience in each case study. The workshops followed the structure detailed in Table 3. Firstly, the moderator explained the resilience principles and related attributes. Next, participants scored the importance of attributes for the resilience of their case studies on a scale from 1 (not very important) to 10 (very important). Finally, participants were asked to justify their scores and to discuss them with one another. After the discussion, participants were asked to score again. The scores from this second round were retained. The participants were asked to score 18 of the 21 attributes. The scores given to Infrastructure capital were used to weigh *Farm infrastructure* and *Infrastructure in the living area*. The scores given to Social capital were used to weigh the attributes *Social support*, *Honours legacy* and *Work and quality of life*.

Participants (6–10 per workshop) were recruited using a quota sampling method (Pace, 2021) to achieve a broad vision of each case study. These included farmers, farm technicians, veterinarians and representatives of the farmer associations and/or cooperatives participating in the RUMIRES Project. More information about workshop participants can be found in Supplementary Table S4. The workshops, which took place between May and June 2022, were video-recorded and lasted 2–3 h each.

Calculation of scores and weights

Attribute scores

Firstly, for each indicator, we computed a minimum–maximum (**min–max**) normalisation across farms (Eq. (1). In a few cases where numerical indicators were not normally distributed, we removed outliers before normalising. The normalisation process yielded values for each indicator that ranged from 0 (the lowest value in the sample) to 1 (the highest value in the sample).

$$I^c_{if} = \frac{x^c_{if} - min_f(x_i)}{max_f(x_i) - min_f(x_i)} \quad (1)$$

where I^c_{if} is the value obtained for indicator i (i = 1,…,85) of farm f (f = 1,…, 144) in case study c (c = 1,…,3); x^c_{if} is the initial value of indicator i of farm f in case study c; $min_f(x_i)$ and $max_f(x_i)$ are the minimum value and the maximum value of x_{if} across farms f, respectively.

Secondly, we aggregated all indicators assigned to an attribute (Table 1). The result was min–max normalised following Eq. (2). As a result, we obtained a composite score for each attribute, which is referred to as attribute score hereafter. The attribute scores ranged from 0 (the lowest value in the sample) to 1 (the highest value in the sample).

$$AS^c_{af} = \frac{x^c_{af} - min_f(x_a)}{max_f(x_a) - min_f(x_a)} \quad (2)$$

where AS^c_{af} is the attribute score obtained for attribute a (a = 1,…,21) of farm f (f = 1,…, 144) in case study c (c = 1,…,3); x^c_{af} is the sum of the indicators used as proxies of an attribute a of farm f in case study c; $min_f(x_a)$ and $max_f(x_a)$ are the minimum value and the maximum value of x_a across farms f, respectively.

Table 1
Principles, attributes and indicators used in the study to assess resilience attributes in small ruminant farms.

Principle (5)	Attribute (21)	Attribute indicators (85)
1. System reserves	1. Financial capital	1.1. Access to loans
	2. Access to natural capital	2.1. Total number of hectares for forage; 2.2. Grazing surface per animal; 2.3. Percentage of owned surface to feed the herd; 2.4. Use of communal pastures to feed the herd; 2.5. Percentage of arable surface to feed the herd
	3. Farm infrastructure	3.1. Distance to a slaughterhouse or gathering centre[1]; 3.2. Percentage of relevant buildings built in the last 10 years; 3.3. Percentage of relevant buildings renovated in the last 10 years; 3.4. Percentage of relevant machinery bought in the last 10 years; 3.5. Automatic systems available to feed animals
	4. Infrastructure of the living area	4.1. Medical centre available in the town of the farm's location; 4.2. Distance to a hospital[1]; 4.3. Existence of shops in the town of the farm's location; 4.4. Existence of a school in the town of the farm's location; 4.5. Existence of a secondary education school in the town of the farm's location; 4.6. Access to the Internet and a phone signal
	5. Human capital	5.1. Percentage of AWU aged under 40; 5.2. Highest level of education; 5.3. Learning farm skills from predecessors; 5.4. Agricultural education 5.5. Learning from consultants
	6. Social support	6.1. Percentage of AWU of family members; 6.2. Secured farm succession
	7. Honours legacy	7.1. Start farming through inheritance; 7.2. Traditional livestock farming family; 7.3. Traditionally sheep or goat farming family
	8. Work and quality of life	8.1. Average of non-working hours per day a year; 8.2. Average of free days per week; 8.3. Number of holiday days per year; 8.4. No health problems that prevent a farmer from working; 8.5. Number of animals on farm per AWU[1]
2. Diversity	9. Functional diversity	9.1. Mixed crop-livestock farm; 9.2. Transformation of the main product on the farm; 9.3. Number of livestock species other than reared small ruminants; 9.4. Number of different surfaces used for feeding animals[2]; 9.5. Number of products sold; 9.6. Percentage of family income made from non-agricultural activities
	10. Response diversity	10.1. Grazing land or crops available to feed livestock next to the farm; 10.2. Percentage of distribution channels currently used with alternative options; 10.3. Percentage of feed supply channels currently used with alternative options; 10.4. Possibility of selling products directly to consumers; 10.5. No contracts that prevent switching buyers; 10.6. No mandatory buyer requirements to accept products; 10.7. No contracts that prevent switching providers
3. Modularity	11. Spatio-temporal heterogeneity	11.1. Grazing in different geographical areas; 11.2. Number of different surfaces used for feeding animals[2]; 11.3. Number of months per year that feed is bought
	12. Optimally redundant	12.1. Total number of purchasers of the main products; 12.2. Total number of suppliers for animal feed; 12.3. Distribution of calving at various times of the year; 12.4. Number of AWU; 12.5. Number of AWU per animal
	13. Globally autonomous	13.1. Number of months per year that feed is not bought on the farm; 13.2. Percentage of livestock feed produced on the farm; 13.4. Percentage of energy used from renewable sources[3]; 13.5. Percentage of farm income that does not come from subsidies
	14. Sanitary isolation	14.1. Distance to the nearest farm; 14.2. No pastures shared with other flocks of any species; 14.3. No areas shared with wildlife; 14.4. Implementation of quarantines to introduce animals into livestock; 14.5. Periodic analysis of the sanitary water quality
4. Openness	15. Organised and structured sector	15.1. Percentage of data collected on the farm that are shared with other entities; 15.2. Number of livestock association/institution memberships
	16. Knowledge and innovation networks	16.1. Regular participation in sector forums or meetings; 16.2. Participation in research or educational projects; 16.3. Number of channels to obtain sector news
5. Tightness of feedbacks	17. Exposed to disturbances	17.1. Time working as a farmer; 17.2. Years the farm has operated
	18. Organisations' feedback	18.1. Level of trust in the institutions to which a farmer belongs; 18.2. Level of participation in the institutions to which a farmer belongs; 18.3. Level of usefulness of the institutions to which a farmer belongs
	19. Locally interdependent	19.1. Livestock work in collaboration with other farmers; 19.2. Equipment/infrastructure shared with other farmers; 19.3. Dialogue on common problems with other farmers; 19.4. Percentage of products sold directly to consumers; 19.5. Percentage of products sold at local markets/fairs; 19.6. Percentage of product sold with a quality label; 19.7. Number of non-livestock sectors with which the farmer cooperates
	20. Ecologically self-regulated	20.1. Livestock grazing in conservation areas; 20.2. Possibility to feed herds using only local resources if necessary; 20.3. Percentage of grazed forage area
	21. Coupled with natural capital	21.1. Number of months per year with livestock on pasture; 21.2. Percentage of natural pasture area used for feeding; 21.3. Percentage of water used on the farm that comes from natural sources; 21.4. Percentage of energy used from renewable sources[3]; 21.5. Percentage of livestock by-products used in nearby areas

Abbreviations: AWU = Annual Working Units.
[1] Lower values correspond to higher resilience. Values were reverted accordingly in further calculations (see Supplementary Table S3).
[2] Indicator assigned as a proxy for Functional diversity and Spatio-temporal heterogeneity.
[3] Indicator assigned as a proxy for Globally autonomous and Coupled with natural capital.

Attribute weights

We calculated the attribute weights using a budget allocation process, where stakeholders' perceived importance of attributes was assigned a particular budget in a case study (OECD, 2008). The sum of all weights per case study was 100. The obtained values, referred to as attribute weights hereafter, were used to weight attribute scores in the final overall score. Attribute weights were calculated using Eq. (3).

$$AW_a^c = \frac{\sum \left(\frac{x_{as}^c}{\sum_{a=21} x_{as}^c} \times 100 \right)}{n^c} \quad (3)$$

where AW_a^c is the value of the attribute weight of attribute a (a = 1,...,21) in case study c (c = 1,..., 3); x_{as}^c is the score of the importance attached to attribute a by stakeholder s (s = 1,..., n^c) in case study c; n^c is the number of stakeholders in the workshop held in case study c.

Table 2
Description of the small ruminant farms sampled (n = 144).

Case study	Meat sheep	Dairy sheep	Dairy goat
Number of surveys	50	41	53
Farmer's age (Mean ± SD)	49.0 ± 10.59	48.2 ± 9.57	46.3 ± 10.82
Farmer's gender (% female)	14.0	31.7	15.1
Herd size (Mean ± SD)	983.9 ± 602.51	301.0 ± 113.69	481.4 ± 269.45
Grazing months (Mean ± SD)	11.2 ± 1.71	10.3 ± 1.33	4.8 ± 5.42
Hectares per animal (Mean ± SD)	1.0 ± 0.75	0.2 ± 0.12	0.1 ± 0.16
Percentage of purchased feed out of the total used feed (Mean ± SD)	44.6 ± 24.13	83.8 ± 18.35	92.7 ± 15.65
Mixed crop-livestock system (% farms)	74.0	9.8	37.7
Processing the main product[1] (% farms)	2.0	82.9	11.3
Farm income from subsidies (%)	37.6 ± 12.60	19.7 ± 8.72	7.6 ± 8.63

[1] Refers to the on-farm processing of lamb/kid and/or milk into a product that is ready to sell to consumers, i.e. lamb/kid meat or dairy products.

Table 3
Structure of participatory workshops to assess attributes' importance (weights) for resilience in the small ruminant case studies.

Research question	Steps	Format	Scoring
What is the importance of attributes for building resilience in each case study?	1. Explanation of the meaning and contribution to resilience of the attributes linked with a principle[1]	Moderator's explanation	–
	2. Assessing attributes' importance for resilience[1]	Filling in a form individually	From 1 to 10, where; 1: not very important, 10: very important
	3. Discussion of attributes' importance for resilience[1]	Plenary discussion	–
	4. Assessing attributes' importance after discussion[1]	Filling in a form individually	From 1 to 10, where; 1: not very important, 10: very important

[1] Steps followed 5 times, one for each resilience principle (Table 1).

Overall resilience score

The overall resilience score was computed by the sum of the weighted averages of the attribute scores and weights (OECD, 2008) (Eq. (4).

$$RS_f^c = \sum_{a=21} \left(AS_{af}^c \times AW_a^c \right) \quad (4)$$

where RS_f^c is the value of the resilience score obtained of farm f in case study c; AS_{af}^c is the value of the attribute score obtained of farm f for attribute a in case study c; AW_a^c is the attribute weight obtained for attribute a in case study c.

Comparisons among case studies

To understand the strengths and weaknesses of farm resilience in each case study, we compared the results found in all three case studies using a non-parametric Kruskal-Wallis test and a *posthoc* Dunn's test using R (Kruskal and Wallis, 1952; Dunn, 1964; Parab and Bhalerao, 2010). Those statistical tests are suitable when data are not normally distributed, and when data include categorical variables. The Kruskall-Wallis test shows whether there are statistical differences in medians across case studies, and Dunn's test performs multiple pairwise comparisons to find statistical differences between case studies.

Results

Attribute indicators

Descriptive statistics revealed that some indicators yielded similar values across case studies, while others were statistically different from each other (Supplementary Table S3). For example, the indicators measuring *Human capital* (Indicators 5.3 and 5.5.) or *Organisations' feedback* (Indicators 18.1, 18.2 and 18.3) obtained similar values across case studies. The indicators measuring the attributes related to natural resources availability and use exhibited the largest differences among the case studies. For instance, regarding *Access to natural capital*, the maximum value of "Total number of hectares for forage" (Indicator 2.1.) in the meat sheep case (i.e. 2 642 ha) was considerably larger than in the other two cases (i.e. 138 ha for dairy sheep and 250 ha for dairy goats).

Attribute scores

Table 4 presents attribute scores across case studies. The distribution of scores is graphically represented in Supplementary Figure S1. Few attributes had similar scores across the case studies. The median values of the *Financial capital*, *Knowledge and innovation networks* and *Organisations' feedback* scores were above 0.6 in all the case studies. The *Farm infrastructure*, *Social support* and *Spatio-temporal heterogeneity* scores were below 0.5. Contrarily, most attributes obtained different scores in each case. For the meat sheep case, the *Access to natural capital* and *Honours legacy* scores were higher than in the dairy sheep and dairy goat cases; *Work and quality of life* was lower than in the other case studies. Regarding dairy sheep, *Organised and structured sector* was higher and *Optimally redundant* was lower than in meat sheep and dairy goat cases; the *Human capital* scores were significantly higher than on meat sheep farms. In the dairy goat case, *Infrastructure of the living area* and *Sanitary isolation* were higher than on the meat sheep and dairy sheep farms. *Access to natural capital*, *Functional diversity*, *Response diversity*, *Globally autonomous* and *Exposed to disturbances* were significantly lower than in the other case studies. The median scores of *Locally interdependent*, *Ecologically-self regulated* and *Coupled with natural capital* were also lower in the dairy goat case study compared to dairy and meat sheep case studies.

Attribute weights

The values in Fig. 3 show the attribute weights results across case studies. For most attributes, weights were not significantly

Table 4
Mean and median attribute scores in the small ruminant case studies.

Attribute scores	Meat sheep		Dairy sheep		Dairy goat	
	Mean ± SD	Median	Mean ± SD	Median	Mean ± SD	Median
Financial capital[1]	0.96 ± 0.198	1.00	0.88 ± 0.331	1.00	0.96 ± 0.185	1.00
Access to natural capital	0.47 ± 0.195	0.46 [a]	0.33 ± 0.150	0.37 [b]	0.14 ± 0.179	0.02 [c]
Farm infrastructure	0.47 ± 0.200	0.46	0.41 ± 0.189	0.42	0.38 ± 0.191	0.41
Infrastructure of the living area	0.66 ± 0.228	0.72 [a]	0.64 ± 0.272	0.75 [a]	0.85 ± 0.168	0.91 [b]
Human capital	0.60 ± 0.173	0.60 [a]	0.70 ± 0.148	0.76 [b]	0.61 ± 0.210	0.63 [ab]
Social support	0.30 ± 0.221	0.27	0.32 ± 0.256	0.31	0.27 ± 0.278	0.25
Honours legacy	0.85 ± 0.287	1.00 [a]	0.67 ± 0.380	0.67 [b]	0.63 ± 0.347	0.67 [b]
Work and quality of life	0.46 ± 0.206	0.48 [a]	0.57 ± 0.156	0.58 [b]	0.58 ± 0.171	0.61 [b]
Functional diversity	0.47 ± 0.186	0.50 [a]	0.55 ± 0.190	0.60 [a]	0.35 ± 0.211	0.36 [b]
Response diversity	0.62 ± 0.263	0.56 [a]	0.64 ± 0.204	0.56 [a]	0.39 ± 0.201	0.33 [b]
Spatio-temporal heterogeneity	0.44 ± 0.176	0.40	0.37 ± 0.159	0.37	0.37 ± 0.079	0.33
Optimally redundant	0.44 ± 0.122	0.44 [a]	0.28 ± 0.171	0.25 [b]	0.50 ± 0.150	0.49 [c]
Globally autonomous	0.37 ± 0.199	0.34 [a]	0.32 ± 0.142	0.31 [a]	0.19 ± 0.123	0.14 [b]
Sanitary isolation	0.26 ± 0.208	0.25 [a]	0.34 ± 0.189	0.29 [a]	0.58 ± 0.213	0.61 [b]
Organised and structured sector	0.60 ± 0.359	0.79 [a]	0.80 ± 0.145	0.80 [b]	0.64 ± 0.194	0.68 [a]
Knowledge and innovation networks	0.63 ± 0.302	0.77	0.68 ± 0.195	0.75	0.59 ± 0.247	0.68
Exposed to disturbances	0.67 ± 0.237	0.71 [a]	0.63 ± 0.204	0.65 [a]	0.40 ± 0.233	0.40 [b]
Organisations' feedback	0.67 ± 0.250	0.72	0.67 ± 0.175	0.68	0.67 ± 0.242	0.70
Locally interdependent	0.44 ± 0.196	0.43 [a]	0.54 ± 0.185	0.53 [a]	0.24 ± 0.169	0.20 [b]
Ecologically self-regulated	0.75 ± 0.171	0.67 [a]	0.61 ± 0.223	0.58 [a]	0.25 ± 0.288	0.19 [b]
Coupled with natural capital	0.61 ± 0.174	0.59 [a]	0.66 ± 0.147	0.65 [a]	0.43 ± 0.304	0.38 [b]

Values within a row with different superscripts differ significantly at $P < 0.05$.
[1] The value of mean corresponds to the proportion of farmers who answered "Yes".

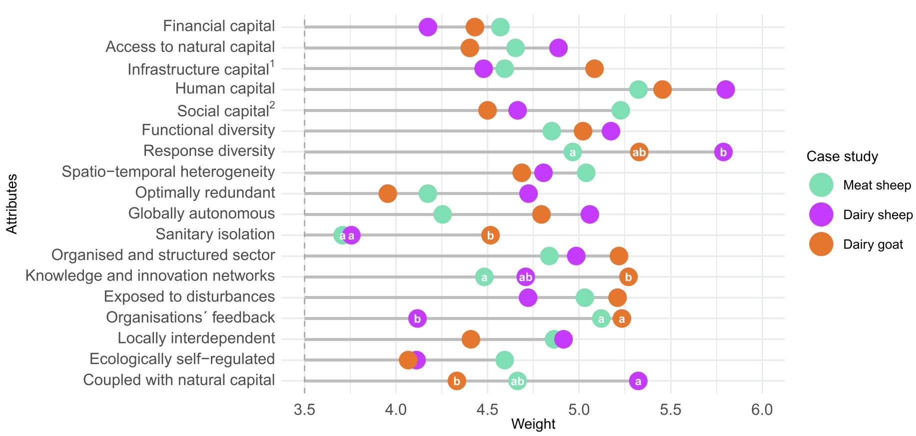

Fig. 3. Attribute weights in the small ruminant case studies. The represented minimum and maximum values equal 3.71 and 5.80, respectively. [1] Infrastructure capital was used to weigh the attributes Farm infrastructure and Infrastructures in the living area; [2] Social capital was used to weigh the attributes Social support, Honours legacy and Work and quality of life (see Section 2.4.2). For all the attributes with a different letter, the difference between medians was statistically significant ($P < 0.05$) according to Dunńs test.

different across case studies. *Human capital* was the most important attribute across all cases and *Sanitary isolation* was considered less important than other attributes, especially for the dairy and meat sheep cases.

In the meat sheep case, the weight of *Response diversity* was lower than in dairy sheep. In turn, the weight for *Organisations' feedback* was significantly lower in dairy sheep than in meat sheep and dairy goats. In the dairy goat case study, the *Sanitary isolation* weight was significantly higher than in dairy or meat sheep and the *Knowledge and innovation networks* weight was higher than in meat sheep. Finally, *Coupled with natural capital* was significantly lower in dairy goats than in dairy sheep.

The overall resilience score

Farms obtained overall resilience scores between 30 and 70 (Fig. 4). In general, the median scores for the meat and dairy sheep farms were significantly higher than the scores of the dairy goat farms. Although the median value was similar in both sheep farm types, the distribution of the scores in meat sheep was wider than on the dairy sheep farms. Dairy goat farms showed the widest distribution.

Fig. 5 shows the contribution of attributes to the resilience score in each case study. The attributes that contributed the most were: *Honours legacy* in the meat sheep farms, *Human capital* in the dairy sheep farms, and *Infrastructure of the living area* in the dairy goat farms. *Financial capital* is the second attribute that contributed most to the resilience score in the three case studies. *Organised and structured sector* is the third attribute in meat and dairy sheep farms. In contrast, the attributes that contributed less were: *Sanitary isolation* in the meat and dairy sheep farms, and *Access to natural capital* in the dairy goat farms. Other attributes that contributed little to the resilience score were: *Social support* and *Globally autonomous* in meat sheep farms, *Optimally redundant* and *Social support* in dairy sheep farms, and *Ecologically self-regulated* and *Globally autonomous* in dairy goat farms.

Fig. 4. Distribution of the overall resilience scores in the small ruminant case studies. Each box displays the first (the lower frame) and the third (the upper frame) quartiles, as well as the median (the horizontal line in the box). Violin plots are computed following Kernel density estimations based on Gaussian smoothing and a bandwidth adjustment equalling 1. The letters on the plot indicate significant differences; different letters denote that the difference among the medians of case studies is statistically significant according to Dunńs Test at the $P < 0.05$ significance level.

Discussion

Implications for the case studies

Status of the resilience attributes

Fig. 6 summarises the main findings, which are discussed in detail in the subsequent sections. For meat sheep farms, we found that *Access to natural capital* and social capital (i.e. *Honours legacy*) were major strengths, while *Work and quality of life* was a significant weakness for farms. The highest *Access to natural capital* in the meat sheep farms can be attributed to the agroecological characteristics of the region (Pardos et al., 2008). First, rainfed agriculture is predominant in this region, where sheep farming and cereal crops have traditionally complemented each other (sheep can use the byproducts of agriculture such as straw and stubble). Second, farmers can access pastures that extend over large areas in the landscape.

The meat sheep case scored the highest for *Honours legacy*, which can be attributed to the large proportion of farmers taking over the farm from their predecessors. Family ties to farming are associated with successful farm succession because the family plays a key role in providing knowledge, experience and attachment to the farm (Bertolozzi-Caredio et al., 2020). Family succession is a major contributor to resilience, as farmers develop an emotional attachment to farming, which encourages them to continue despite low profitability or poor quality of life (Bertolozzi-Caredio et al., 2020; Stotten, 2020). Meat sheep farms showed low *Work and quality of life* levels compared to the other case studies. This is linked to shepherding, which requires long periods of time walking to pastures and supervising the flock (Paas et al., 2021b).

On dairy sheep farms, we found that sector organisation (i.e. *Organised and structured sector*) was a major strength, while the redundancy of management alternatives (i.e. *Optimally redundant*) was a significant weakness. Compared to the other case studies, the dairy sheep farms were embedded in a more *Organised and structured sector* with several organisations that support farmers in different technical and economic aspects (e.g. genetics or product marketing). Examples of those organisations include breeders associations, farmers cooperatives and the PDO '*Idiazabal*' (Ruiz et al., 2010). This facilitates collaboration between farmers, other stakeholders, and consumers with common interests (Pulina et al., 2018).

Optimally redundant was a weakness of dairy sheep. Their management is very seasonal: use of mountain pastures in spring and summer, lambing in winter, and milking in spring and even summer (Ruiz et al., 2010). Any event that could diminish pasture production (e.g. drought) or affect sheep health (e.g. abortive diseases) would significantly affect the productivity of the farms. Additionally, *Human capital* emerged as a strength of the dairy sheep case. This may be linked to the professionalisation of the sector, which is higher in the dairy small ruminant systems than in the meat ones (Belanche et al., 2021).

For dairy goat farms, the services of the rural areas (i.e. *Infrastructure of the living area*) and the biosecurity (i.e. *Sanitary isolation*) were major strengths, while autonomy (i.e. *Globally autonomous*), diversity (i.e. *Functional diversity* and *Response diversity*) and the attributes related to the availability of natural resources represented a significant weakness. The *Infrastructure in the living area* was better in Andalusia than in the other case studies, which reflects the differences between territories in Spain for accessing basic services (Goerlich et al., 2021). In Andalusia, the average distance to hospitals, supermarkets and schools is much shorter than in Aragón (meat sheep case) and the Basque Country (dairy sheep case), especially in mountain areas (Goerlich et al., 2021). Another strength of dairy goat farms was their *Sanitary isolation*, which is related to farms where flocks are kept indoors. This facilitates the

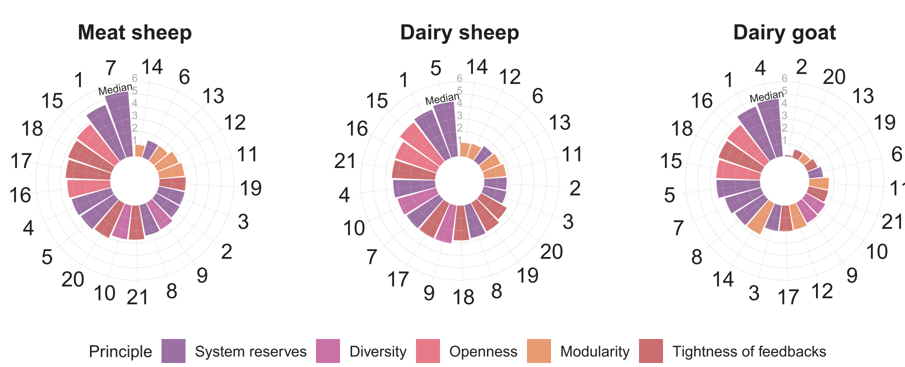

Fig. 5. Contribution of attributes to the overall resilience score in the small ruminant case studies. Bars represent the median value of each attribute. Numbers around the circular graph represent the attribute names: 1. Financial capital, 2. Access to natural capital, 3. Farm infrastructure, 4. Infrastructure of the living area, 5. Human capital, 6. Social support, 7. Honours legacy, 8. Work and quality of life, 9. Functional diversity, 10. Response diversity, 11. Spatio-temporal heterogeneity, 12. Optimally redundant, 13. Globally autonomous, 14. Sanitary isolation, 15. Organised and structured sector, 16. Knowledge and innovation networks, 17. Exposed to disturbances, 18. Organisations' feedback, 19. Locally interdependent, 20. Ecologically self-regulated, 21. Coupled with natural capital. The colours represent the classification of attributes into principles according to Table 1.

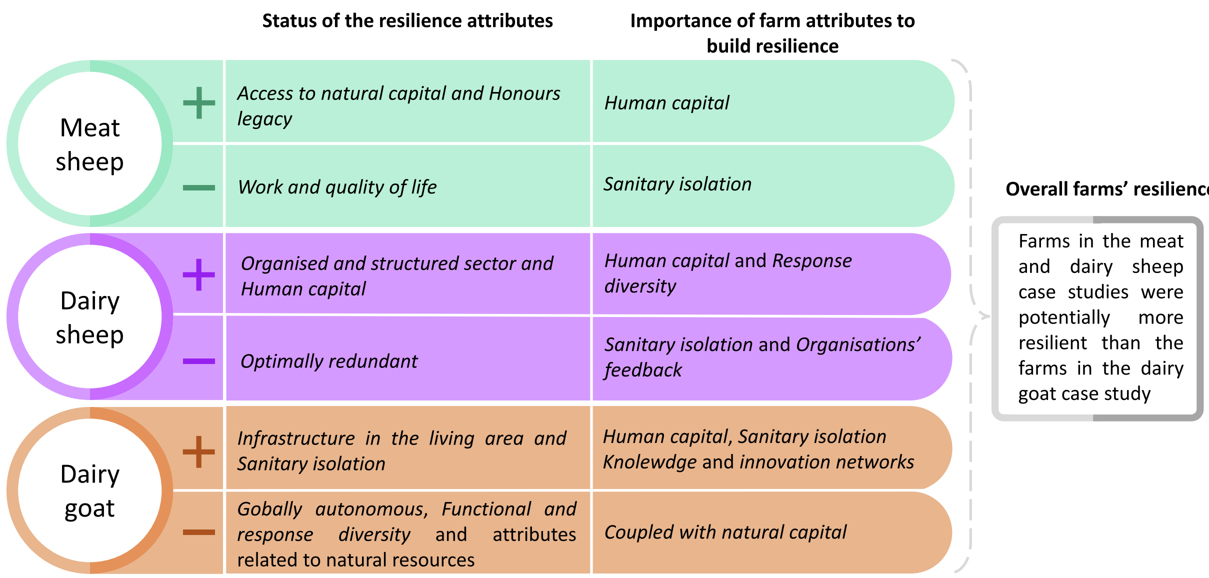

Fig. 6. Summary of the implications for the small ruminant case studies. For each case study, the attributes that showed significant implications are classified into four boxes. Columns refer to (1) the status of resilience attributes (attribute scores) and (2) the importance of farm attributes to build resilience in each case study (attribute weights). Rows with (+) and (−) contain the attributes that obtained higher and lower values. The box at the right shows the overall farm̃s resilience.

implementation of biosecurity measures to prevent diseases, which is not easy when animals are kept outdoors (Jori et al., 2021).

A significant weakness of dairy goat farms was the lack of autonomy, which is explained by their limited capacity to produce on-farm feed. This may hamper their competitiveness due to their exposure to price volatility (Pulina et al, 2018; Morales-Jerrett et al., 2022). Dairy goat farms exhibited lower functional and response diversity, which could be explained by their orientation towards milk production with no further processing (Morales-Jerrett et al., 2022). Dairy goat farmers in Andalusia have limited options for selling directly to consumers because milk is usually processed into dairy products before being consumed (Miller and Lu, 2019). Dairy goat farms being less *Exposed to disturbances* can be related to the fewer years that farmers spent working as farmers compared to the other case studies. Similar processes have been identified in France, where people started dairy goat farming and switched to non-agricultural activities or retired when circumstances are unfavourable (CNE, 2023). Finally, dairy goat farms were less *Locally interdependent*. This can be explained by their limited interaction with local agents and the few farmers who sell products with quality labels, which is caused by the lack of labels that confer their products local recognition (Morales-Jerrett et al., 2022). Several attributes linked with the use of natural resources revealed a higher degree of heterogeneity and lower scores compared to the other case studies. Dairy goat farms had less *Access to natural capital* and were less *Ecologically self-regulated* and less *Coupled with natural capital*. Many farms cannot rely on natural resources, so a diversity of farms co-exist that range from purely intensive to different grazing intensity levels (Morales-Jerrett et al., 2022). There is fierce competition for agricultural land in Andalusia due to olive trees covering half the arable land in the region (MAPA, 2019), other agricultural activities, and legal limitations to use protected natural areas. As a result, land price is higher than in other Spanish regions (MAPA, 2022b).

Importance of farm attributes to build resilience

Human capital particularly emerged as one of the most relevant resilience attributes (Fig. 6). This reinforces the fact that the human dimension of farming (e.g. farmer skills) is key for building farm resilience (Anuradha et al., 2021; Le Goff et al., 2022). Yet, the degree to which farm resilience is built through other attributes varied among the case studies. *Sanitary isolation* was especially important for dairy goats as discussed above. *Response diversity* was more important for dairy sheep than for meat sheep. The flexibility to produce a variety of dairy products is a strategy to deal with sector-specific challenges, such as volatile milk prices (Pulina et al., 2018; Snorek et al., 2023). Access to *Knowledge and innovation networks* was particularly valued in the dairy goat case study. Innovations are important to improve performance when the main income from milk and the economic margin are tight (De-Pablos-Heredero et al., 2020).

Less importance was attached to feedback between organisations and farmers (i.e. *Organisations' feedback*) in dairy sheep. This is particularly interesting because the sector is highly organised and structured. Organisations contribute to resilience by increasing coordination and knowledge flow (Manyise and Dentoni, 2021; Soriano et al., 2023). However, some stakeholders argued that organisations sometimes restrict farmers' flexibility to go beyond predesigned strategies (e.g. milk quality improvement programmes), and organisations' influence on farmers' decisions can hinder resilience. Finally, the less importance attached to being *Coupled with natural capital* with dairy goats is in line with their low use of natural resources, as discussed in the previous section.

Overall farms' resilience

A higher proportion of farms in the dairy sheep and dairy meat case studies scored higher resilience than farms in the dairy goat case study (Fig. 6). This was mainly driven by the lower availability and use of natural resources. In addition, dairy goat farms revealed the greatest heterogeneity within the case study, which can be seen as a strength at the sector level in this region (Morales-Jerrett et al., 2022). By exploring the attributes that contribute the most or least to the resilience scores, we understood what built resilience in each case study (Fig. 5). Access to loans (i.e. *Financial capital*) was key across cases, meaning that the majority of farms could access additional funding if needed. This can be positive for the adaptation capacity of farms (Kgosikoma et al., 2018; Tessema and Simane, 2019).

The resilience of meat sheep farms was mainly built by farmers' emotional attachment to farming (i.e. *Honours legacy*) and a solid sector organisation, which helps to structure farming activities (i.e. management innovations and trade of inputs and lambs). However, meat sheep farms could increase their resilience by reducing their exposure to wildlife diseases, increasing social support in farming and achieving a higher autonomy on farms by reducing their economic dependence on CAP subsidies. Implementing these changes may require adaptation and transformation of farms (Bertolozzi-Caredio et al., 2021; Paas et al., 2021b) and may reduce the robustness provided by CAP subsidies (Slijper et al., 2022).

The resilience of dairy sheep farms was mainly built by human capital (i.e. skilled farmers) and, similarly to meat sheep, by a solid sector organisation. Similarly to the meat sheep farms, dairy sheep farms could increase their resilience by reducing their exposure to wildlife diseases and increasing social support. Additionally, these farms could improve their distribution of production seasons (i.e. Optimally redundant), for example, by adapting their management to extend the calving season and spread production over longer periods.

Finally, the resilience of dairy goat farms was built by the infrastructure in the area where farmers and their families live, which is key for farmers' livelihoods and their connection to various networks. In contrast, dairy goat farms lacked several attributes related to access and use of natural resources, as well as feed autonomy. Improving their resilience would require greater access to land and increased on-farm feed production. These changes would require a transformation of the current land use in Andalusia to ease the integration of livestock and other land uses.

Methodological considerations

Our approach operationalises the assessment of resilience attributes on livestock farms. It recognises that resilience is a property shaped by the context in which a farm is embedded (Quinlan et al., 2016). In this sense, the attribute and resilience scores can be a useful tool for technicians and policymakers, as they provide a benchmark that can vary over time. The scores integrate a wide range of indicators, reducing potential bias, and can be flexible to include new indicators or attribute weights that allow to better reflect the reality in particular contexts. In addition, the approach is feasible across many farms as it is specifically designed to enable data collection in real farm conditions, i.e. a set of defined indicators that can be collected in a short time.

The single overall resilience score per farm can guide policy (OECD, 2008) by making resilience easy to interpret. Resilience metrics can help maintaining or moving farms towards more desirable states, track potential levers and evaluate how the system is being managed (Quinlan et al., 2016; Quandt and Paderes, 2023). For example, resilience metrics based on scores are used to assess household resilience in developing countries (FAO, 2016). Therefore, the overall resilience score provides a standardised and quantified value that reflects farms' potential resilience to cope with challenges. Nonetheless, by combining all the attributes into a single score, we assume that they are additive, and we obviate their interaction. We acknowledge this is a simplification of reality as attributes may interact in different ways to confer farm resilience (Perrin et al., 2024). Thus, the individual interpretation of attributes is still necessary to understand the underlying factors of resilience in each farm, and the synergies or trade-offs that cannot be reflected in a single overall score. For instance, *Coupled with natural capital* may be associated with lower *Sanitary isolation* because grazing practices may reduce the ability to isolate animals from diseases spread by wildlife. Additionally, improving the attributes on farms would require examining the underlying indicators that build the attribute scores.

Although using indicators to assess resilience is considered an objective approach, the way these indicators are measured is always a continuum between objectivity and subjectivity (Jones, 2018). In this regard, the collection of indicators through surveys is a potential source of bias, as farmers' responses can influence the value of the indicator according to their own understanding. For this reason, it is important to measure indicators in their most meaningful unit.

Some indicators are context-specific to our case studies, such as "Grazing in different geographical areas", but many can be applied to other agricultural systems. Some indicators may not be directly related to resilience without considering agroclimatic conditions or management practices (e.g. "Total number of hectares for forage" or "Mixed crop-livestock farm"). Addressing these nuances and including more farm management indicators could sharpen the approach. However, this would require deeper analysis to apply the indicators in different contexts and would add complexity. It should also be noted that results are relative, i.e. a farm with moderate resilience may achieve a high score in a sample where most farms prove to be poorly resilient. To address this, it is necessary to consider a wide number of farms per case study, covering as much variability as possible.

The selection of attributes and indicators was a top-down, expert-driven approach. This can be seen as a weakness, as the contextual factors driving resilience might not be reflected in the selection of indicators (Jones, 2018; Quinlan et al., 2016; Quandt and Paderes, 2023). In this regard, we considered many attributes and indicators that potentially contribute to general resilience to avoid potential biases, but others may be missing. However, we are confident that our approach is: (i) grounded in the literature; (ii) agreed by stakeholders during workshops; and (iii) tested and adjusted based on feedback from researchers and stakeholders.

Future research

Our research aim was the ex-ante quantification of general resilience. However, the ability to cope with future challenges (i.e. the revealed resilience) needs longitudinal studies to confirm whether different indicators predict farm resilience. Other research could also be directed to identifying the thresholds and optimal levels of attributes and indicators, which could constitute targets for decision makers. More studies are also needed to find what are the best indicators of resilience to lower their number so that assessments become more operative. Further studies could also investigate alternative ways to aggregate indicators, for example, based on decision support systems (Sadok et al., 2009). Finally, future assessments should investigate the trade-offs between different resilience attributes and indicators.

To enable resilience policies, some indicators should be included in current standardised data-recording protocols (i.e. Farm Sustainability Data Network; European Commission, 2022), especially those that can be improved. Thus, we acknowledge that some indicators cannot be changed because they are implicit to farms (e.g. number of years working as a farmer or start farming through inheritance). However, some indicators, such as distance to supermarkets, education and health services, the existence of farm successors or the availability of pastures, are especially relevant in the resilience realm. Farms are embedded in rural areas where infrastructures are essential for families' well-being. Given that the indicators related to distances to basic services are readily available in national databases, the lack of infrastructures for family farms could be addressed. It is also necessary to address farm succession more accurately. The identification of farms with succession problems should lead to specific policy measures that encourage new farming entries. For instance, they could help to increase the agricultural sector's attractiveness and promote the provision of good advisory services or increase support for innovations (Balmann et al., 2022; Milone and Ventura, 2019). In those areas facing difficulties to access land, farmers would benefit from institutional support to promote synergies between different agricultural activities, e.g. forestry and livestock (Low et al., 2023). Novel regulations that ease the transformation of farm products and the possibility of marketing them directly to consumers could also improve resilience. For example, these regulations could contribute to establish infrastructure, such as local slaughterhouses, which would make it easier for farmers to sell their products directly to consumers in short-chain marketing networks.

Conclusions

Resilience attributes are key for building resilient farms, but elucidating and quantifying resilience attributes is challenging. Our paper contributes to the operationalisation of resilience attributes by taking a practical approach, which was applied empirically to three small ruminant farming systems. We were able to identify the attributes where a particular system performs better or worse than others in resilience terms. We identified the better performance of meat sheep farms in natural and social capital terms, of the dairy sheep case in organisational and human capital terms, and of the dairy goat case in infrastructure in the living areas. The approach can also be applied to other livestock farming systems. Some of the resilience indicators could form part of farm data collection protocols to support private and public decision makers in their efforts to improve the resilience of agriculture.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2025.101566) can be found at the foot of the online page, in the Appendix section.

Ethics approval

The research protocol, workshops, survey questionnaire and data collection were approved by the Ethics Committee for Research with Humans of the Agrifood Research and Technology Centre of Aragón (Ref. CEISH_2022_4).

Data and model availability statement

None of the data were deposited in an official repository but will be available upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used DeepL to check the wording and the spelling of some parts of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Declaration of interest

None.

Acknowledgements

We are thankful for the support of the producer associations that are part of the RUMIRES project (Strengthening the resilience of small ruminant local breed farming systems: from COVID-19 to global change): Oviaragon, sheep farmers' cooperative; Cabrandalucia, Andalusian federation of pure breed goat associations; Acriflor, Florida breed goat association; Cabrama, Malagueña breed goat association; Caprigran, Murciano-granadina breed goat association; Payoya, Payoya breed goat association; P.D.O cheese Idiazabal, protected designation of origin for "Idiazabal" cheese. We thank the veterinary services, farmers and stakeholders who made data collection possible.

Financial support statement

This work was supported by the Spanish Ministry of Science, Innovation and Universities and the Spanish National Agency for Innovation [Project PID2020-120312RA-I00 funded by MICIU/AEI/10.13039/501100011033]. A. Prat-Benhamou was supported by a predoctoral contract from the Government of Aragón. This work was conducted during a research stay in the Business Economics Group of the Wageningen University & Research, supported by a scholarship from the Agri-Food Institute of Aragón (IA2). J. Lizarralde was supported by the Spanish Ministry of Science, Innovation and Universities [PRE2020-095654]. A. Prat-Benhamou, A. Bernués and D. Martín-Collado belong to the "Socio-Ecological Systems" Research Group (A26_23R, Gobierno de Aragón).

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