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Research

Overcoming collapse of farming systems: shifting from vicious to virtuous circles in the extensive sheep farming system in Huesca (Spain)

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ABSTRACT. Farming systems in Europe are perceived by stakeholders as having a low level of resilience and sustainability when confronted with shocks and ongoing stresses. Specifically, European extensive livestock systems are faced with challenges such as low farm income, uncertain policies, and changing meat consumption patterns, which are causing these systems to decline. Focused on the extensive sheep farming system in Huesca (Spain), our aim with this paper is to analyze the dynamics that have driven this system close to collapse and propose strategies that can reverse its dynamics to make the system both resilient and sustainable. This assessment is framed under an integrated resilience and sustainability approach, in which resilience variables (challenges, functions, and resilient attributes) and sustainability dimensions (economic, social, environmental, and institutional) are considered. Drawing on qualitative system dynamics and participatory causal loop diagram mapping, we show that the extensive sheep production system is threatened not only by challenges (e.g., increasing feeding costs), but also by weakly expressed resilience attributes (e.g., lack of diverse policies) and diminished functions (e.g., declining number of farms). There are delayed vicious circles in the system's dynamics that are interrelated across sustainability dimensions, implying that time will be required to reverse the system's dynamics. Hence, to foster the resilience of farming systems, specifically extensive livestock systems, a coordinated range of long-term strategies and policies (agricultural, environmental, sanitary, urban, labor, consumption, and innovation) are needed, aimed at responding to challenges, weak attributes, and diminished functions across different sustainability domains.

Key Words: *extensive livestock system; participatory approach; qualitative system dynamics; resilience; resilience attributes*

INTRODUCTION

Many stakeholders perceive farming systems in Europe as having low resilience and sustainability (Reidsma et al. 2020). In this context, the European Commission's Farm to Fork strategy aims at increasing the resilience and sustainability of European food systems (EC 2020). Specifically, extensive livestock systems in Europe are facing a broad array of environmental, economic, social, and institutional challenges (Belanche et al. 2021) that threaten their stability and possibly push them toward collapse (Xu et al. 2015). A collapse implies an undesirable and abrupt regime shift, which is difficult to predict and manage (Groffman et al. 2006, Kinzig et al. 2006, Scheffer et al. 2009). It also implies a loss of resilience (Holling 2001, Walker et al. 2006, Cumming and Peterson 2017), understood as the ability of a system to maintain its functions even when it is affected by challenges, shocks, or stresses (Darnhofer 2014, Meuwissen et al. 2019). Sustainability refers to the capacity of the system to balance the integration of environmental, economic, and social development (Kharrazi et al. 2019).

Attempting to make systems both resilient and sustainable simultaneously may lead to tensions and complexities in decision making and policy (Lizarralde et al. 2015, Marchese et al. 2018). For example, resilience does not include a long-term dimension, while the core concept of sustainability is intergenerational renewal (Saunders and Becker 2015, Xu et al. 2015). To overcome potential contradictions, resilience and sustainability goals should be managed as complementary outcomes (Saunders and Becker 2015). In this regard, Meuwissen et al. (2020) suggest that the concurrent assessment of resilience and sustainability facilitates the exploration of pathways that a farming system can follow to provide its main functions without disregarding other functions that shape it, while responding to shocks and stresses. The integrated assessment of resilience and sustainability makes it possible to address multi-scale and multi-level challenges (Anderies et al. 2013) and to exploit the complementarity of these two approaches (Bocchini et al. 2014).

Analyzing the resilience and sustainability of a farming system thus inevitably implies exploring system dynamics across time and space (Darnhofer et al. 2010, Herman et al. 2018, Perrin et al. 2020). The assessment of system dynamics allows one to integrate indicators and identify feedback loops within the system. Feedback loops determine system behavior and, therefore, are foundational to reflecting upon a system's resilience (Gallopin 2002, Matthews and Selman 2006, Selman and Knight 2006, Xu et al. 2015). Feedback loops self-regulate system behavior (balancing loops) or incite it (reinforcing loops) toward a desired (virtuous circles) or undesired (vicious circles) transformation (Matthews and Selman 2006, Tidball and Krasny 2014). This type of assessment also makes it possible to identify system delays, i.e., the time lag between a change in one component and its impacts on other components of the system. Analyzing delays in feedback loops is important because they are often the source of imbalances in the system (Sterman 2000) and may help to visualize pressures building up in the system that create abrupt changes when they hit a critical value (Tip 2011).

The system dynamics approach has been widely used and has proved to be useful in analyzing resilience and sustainability because it captures the emergent behaviors and dynamics that characterize complex systems (Fiksel 2006). A number of studies have applied a system dynamics perspective to assess the sustainability of social-ecological systems (Li et al. 2012, Banos-González et al. 2015), natural resources management (Baur and Binder 2015, Sanga and

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Mungatana 2016), and value chain functioning (Lie and Rich 2016). Additionally, other system dynamics studies have focused on resilience assessment of food systems (Brzezina et al. 2016), social-ecological systems (Tenza et al. 2017, Herrera and Kopainsky 2020), and cities (Datola et al. 2022). Although integrated assessment of resilience and sustainability has been previously addressed by applying quantitative (Bocchini et al. 2014) and qualitative methods (Maleksaeidi and Karami 2013, Lizarralde et al. 2015, Saunders and Becker 2015, Xu et al. 2015), the literature lacks studies analyzing sustainability and resilience simultaneously by applying a system dynamics approach, most particularly in farming systems.

To ensure the integrated assessment of resilience and sustainability of a farming system, we follow the resilience assessment framework presented by Meuwissen et al. (2019). In this framework, the relationships between challenges, functions, and resilience attributes are addressed, taking note of the interactions with the economic, social, environmental, and institutional sustainability dimensions of the system, as proposed by Saunders and Becker (2015).

In this paper we focus on the extensive sheep farming system in Huesca (Spain), a system that is close to collapse (Paas et al. 2021a). Ovine production and transhumance practices have long been an important part of the economy in Huesca and a driver of rural population integration (Navarro 1992). Based on a participatory assessment, Paas et al. (2021a) concluded that some of the challenges, functions, and resilience attributes of this system have already reached their critical threshold, indicating an urgent need to reverse this trend. For example, the number of sheep in Huesca has reached its threshold, with a 43.7% reduction since 2005 (MAPA 2022). Reinforcing the resilience of extensive sheep farming systems is key given that extensive livestock systems provide not only private goods, such as ensuring sufficient farm incomes and delivering high-quality food at affordable prices, but also public goods that are not specified as such by other farming systems. Grazing improves soil quality (Peco et al. 2017) and biodiversity (Rodríguez-Ortega et al. 2014, Silva et al. 2019, Ornai et al. 2020), prevents forest fires by keeping the area clean of dry matter (Casasús et al. 2007, Ruiz-Mirazo and Robles 2012) and keeps rural areas attractive (Bernués and Olaizola 2012).

In this context, the aim of this paper is to analyze the dynamics of the extensive sheep system in Huesca that have driven it to near collapse and identify strategies that could reverse these dynamics and turn the system into one that is both resilient and sustainable. Strategies are defined here as the actions needed to be implemented by the actors in the system, actions that shape the system's dynamics and its resilience (Rounsevell et al. 2012). These actions are diverse and may range from using new seeds adapted to climate change and adopted by farmers to developing new financial products targeting farmers' needs and promoted by financial institutions (Soriano et al. 2023).

METHODOLOGY

Case study

This case study investigates the extensive sheep farming system located in Huesca province, Aragón, Northeast Spain. Huesca covers 15,626 km² with two main regions. In the North the Pyrenees and pre-Pyrenees, a mountainous area, cover about 6000 km², with an average annual temperature of 5 °C and 1500 mm of precipitation. Agricultural activity is confined to extensive livestock raising in this area, which often overlaps with protected areas. The southern part of the province is characterized by the plains of the Ebro depression extending approximately 9000 km², with an average annual temperature of 14 °C and 400 mm of precipitation, where extensive/semi-extensive farming (sheep, goat, and cattle), intensive farming (pigs and broiler chickens), and crop farming (rainfed and irrigated) co-exist.

Although traditionally the extensive sheep farming sector was a strong economic motor in this region, it has experienced a drastic decline over the last 20 years (Government of Aragón 2016). The number of farms has decreased from 2902 (1995) to 863 (2022) and the number of sheep from 923,399 (2005) to 347,800 (2022; Government of Aragón 2023a). This system faces a wide range of challenges. In the economic domain, sheep farmers' profits have been negative since 2014, reaching −57.3 €/livestock unit in 2020 (MAPA 2023a). Low productivity partly explains the sector's high dependency on European Union (EU) subsidies (63% of the net value added in 2021; MAPA 2023b), as well as its vulnerability to changing agricultural policy requirements and goals (Milán et al. 2003, Pardos et al. 2008, Soriano et al. 2022).

Farmers in the region also have to manage limited access to pasture lands. There is increasing competitiveness for land, especially in the flat areas of the region. More profitable sectors (e.g., irrigated crops) acquire hectares for cropping, leading to increased land prices, which are not affordable for sheep farmers. In addition, environmental legislation related to wildlife and nature park protection influences access to pasture lands (Buitenhuis et al. 2019). Access to communal mid-mountain areas in the region is limited because they are close to or are part of a protected area (e.g., Sierra y Cañones de Guara Nature Park), where grazing is restricted. Moreover, the inclusion of the Iberian wolf on the list of protected species throughout Spain (MITECO 2023) might lead to less available land because farmers avoid shepherding in areas inhabited by wolves. More frequent and severe droughts are also decreasing the number and the quality of available pastures (Turner 2004, Hernández-Mora et al. 2012).

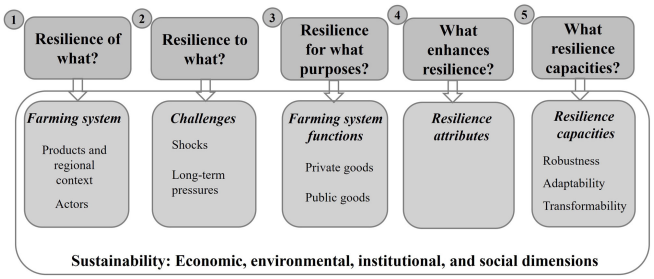
Finally, rural areas in Aragón are also experiencing severe depopulation (Bosque and Navarro 2002; Government of Aragón 2017), the population is ageing, and public investments (schools, medical centers, etc.) are on the decline, factors that discourage family succession and reduce the number of skilled workers (Bertolozzi-Caredio et al. 2020).

Resilience and sustainability assessment framework

Building on the need to integrate resilience and sustainability objectives, the theoretical framework followed in this paper is an extended version of the resilience assessment framework proposed by Meuwissen et al. (2019), which integrates the interdependences between resilience and sustainability. A sustainable system needs to be resilient (Maleksaeidi and Karami 2013) and a resilient system needs to be sustainable (Saunders and Becker 2015).

The framework is dedicated to assessing general resilience, i.e., the capacity of a system to meet all types of challenges, including unknown ones (Folke et al. 2010). It embraces the five resilience questions proposed by Meuwissen et al. (2019), which are answered by considering four sustainability dimensions (Ostrom 2009; Fig. 1).

Fig. 1. Farming system's resilience and sustainability assessment framework. Adapted from Meuwissen et al. (2022).



According to Meuwissen et al. (2019), when assessing resilience, the first question to answer is resilience of what? A farming system is a social-ecological system (Folke et al. 2005, Rounsevell et al. 2012) defined by the main product(s) of interest, the regional context (the local agroecological context, climate conditions, infrastructures, and identity), and the actors involved in them (farmers and any other individuals who have a close mutual connection to them). The second question is resilience to what? Challenges affecting a farming system can be classified into shocks (with an impact over the short term) and long-term pressures. The third question is resilience for what purpose? Functions provided by a farming system can be classified into the provision of private goods (i.e., the provision of food and a reasonable livelihood for people involved in farming) and public goods (i.e., natural resources conservation). The fourth question is what enhances resilience? Resilience attributes are those individual and collective abilities whose presence enables a system's general resilience (Cabell and Oelofse 2012). When these attributes are disappearing or absent, it suggests that the system is moving away from resilience. Appendix I shows the description of the resilience attributes. The fifth question is what resilience capacities? The resilience capacities are robustness (capacity to withstand stresses and [un]anticipated shocks), adaptability (capacity to change the composition of inputs, production, marketing, and risk management in response to shocks and stresses but without changing the structures and feedback mechanisms of the system), and transformability (capacity to significantly change the internal structure and feedback mechanisms of the system in response to either severe shocks or enduring stress that make business as usual impossible, also entailing changes in the functions of the system).

In this study, challenges, functions, and resilience attributes are indicated as "resilience variables" and are analyzed considering their contribution to the economic, environmental, institutional, and social sustainability dimensions. It has been defined that functions are diminished and attributes are weak when they are at or beyond their critical threshold.

The system dynamics approach

The methodological approach used in this paper is based on system dynamics, simulation modeling that is useful to examining the internal mechanisms of a system and feedback loops that drive its outcomes and performance over time (Sterman 2000, Richardson 2011). Wolstenholme (1982, 1999) differentiates between qualitative and quantitative system dynamics. Although quantitative approaches, aided by computer simulation, are often required to anticipate system behavior and evaluate timing, sequencing, and calibration of interventions (Richardson 2011), qualitative approaches can be sufficient to understand the problem and explore potential options for intervention (Wolstenholme 1999, Lane 2001). In this research, a qualitative system dynamics approach is applied to organize observations into a theory or hypothesis of how the system generates the problematic behavior, in this case the decline of the extensive sheep farming system in Huesca. The problematic behavior emerges from the interplay of vicious and virtuous circles and delays in the system (Matthews and Selman 2006). Furthermore, the use of a qualitative system dynamics approach allows delving into the social dimension of the farming system (Hirsch et al. 2007), which is a key dimension in shaping the resilience of social-ecological systems (Soriano et al. 2023).

We use the causal loop diagram (CLD), a tool widely used in system thinking (Bala et al. 2017) and often applied when building diagrams with stakeholders in participatory workshops (Inam et al. 2015). The CLD nomenclature uses arrows to indicate causal links between variables, i.e., whether a variable will cause another variable to change. In a CLD, a cause variable is the variable at the base of the arrow and an effect variable is the variable at the end of the arrowhead. Because a CLD is a qualitative description of the system, the nature of this link is simply indicated by a plus (+) or a minus (−) to indicate if variables move in the same or opposite directions, respectively (Richardson and Pugh 1997). Using this same nomenclature, feedback loops (close circular connections between variables) are identified in the diagram using either an "R" to indicate that variables reinforce each other (reinforcing loop) or a "B" to indicate that variables regulate each other (balancing loop). Delays in the feedback loops are identified by using the symbol "//" on the arrows.

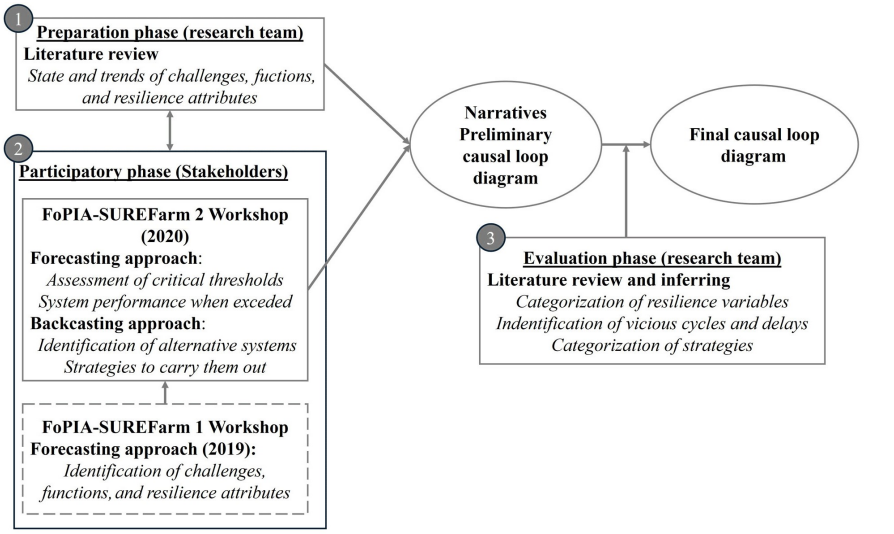
There is not a standard research strategy for generating a system dynamics model (Forrester 1993, Sterman 2000, Walters et al. 2016). In this paper the strategy followed is a participatory approach (Vennix 1996, Tenza et al. 2017, Herrera and Kopainsky 2020), which combines researcher and stakeholder-driven research. The methodology to build the CLD (Fig. 2) follows the three-phases methodology defined by Paas et al. (2021a), consisting of a preparation phase conducted by researchers, a participatory phase with local stakeholders, and an evaluation phase conducted by researchers.

The preparation and participatory phases

The first phase (preparation) mainly consisted of conducting a literature review on the current state and performance of the resilience variables (i.e., challenges, functions, and resilience attributes) of the extensive sheep farming system studied. The second phase (participatory) consisted of the organization of the Participatory Impact Assessment workshop (FoPIA-SURE Farm 2). It was conducted in Huesca on 14 February 2020, with 19 participants, representing different stakeholders of the system under study: farmers (7), veterinarians (3), cooperatives (1), distributors (1), research institutes and universities (3), and the local public authorities (4).

The FoPIA-SURE Farm 2 workshop was built on the previous FoPIA-SURE Farm 1 workshop conducted in Huesca in January 2019. The aim of FoPIA-SURE Farm 1 was to define the

Fig. 2. Methodology to build the causal loop diagram. Adapted from Paas et al. (2021a).



(*) Squares: CLD methodology phases (in bold and underlined), methods (in bold) and activities (in italics); dashed line squares: participatory workshop that is not part of the methodology but indirectly informs the CLD; circles: the results of the methodology.

resilience variables of the system, select their indicators, and evaluate their trends and contributions to the robustness, adaptability, and transformability capacities of the system (Becking et al. 2019, Paas et al. 2019, Reidsma et al. 2020).

The aim of the FoPIA-SURE Farm 2 workshop was to identify the resilience variables at critical thresholds, analyze the interactions between critical thresholds, and assess a possible system decline and the desired alternative systems (Paas et al. 2021a). The activities during the workshop were structured in four steps: Step (1) Assessment of the critical thresholds of the indicators of the system's resilience variables (identified in FoPIA-SURE Farm 1). To this end, the participants were informed of the past trends and current state of the indicators of the resilience variables. Once the meaning of the critical threshold level was explained, the participants were asked to reflect on the relative closeness of the current state of the indicators to their critical threshold ("not close," "somewhat close," "close," and "at/beyond critical threshold"). The participants also provided the value of the critical threshold of resilience indicators when they had such information (Table 1; Step 2) and analysis of the dynamics of the resilience variables when critical thresholds were exceeded. To this end, participants were asked to individually draw a CLD to explain the behavior of the system when the critical thresholds of the challenges, as the main drivers of change, were exceeded. They had a printed template of an empty CLD to draw arrows linking the resilience variables and include the new variables they considered relevant to explaining the dynamics (auxiliary variables). The CLDs built individually served as the basis to design a commonly agreed upon CLD on a blackboard during a plenary session afterwards. Step (3) Identification of possible desired changes of the extensive sheep production system toward the future (desired alternative systems). In a plenary session the participants discussed the desired alternative system or systems that they could foresee for the future (2030). Step (4) Identification of strategies to carry out alternative systems. Participants, organized in small groups, were asked to identify the set of strategies to be implemented to reach the desired alternative system or systems over the long run. Following a backcasting approach, participants freely identified the actions to enable the desired transition, to be performed by each actor in the system, including farmers, cooperatives, technicians, distributors, research institutes, and policy makers. By defining strategies as the actions implemented by the actors in the system, a diverse list of strategies was expected.

The evaluation phase: building the causal loop diagram

The CLD resulting from the FoPIA-SURE Farm 2 workshop was further developed by the research team (without further input from the stakeholders) to add auxiliary variables that would improve clarity and logic to answer the main research questions. First, to show the four sustainability dimensions in the CLD, the research team classified (resilience and auxiliary) variables into economic, social, environmental, and institutional variables. Sustainability dimensions resulted from grouping variables' relationships in the CLD, for example, within the economic dimension groups, the relationships between the economic variables, and the relationships emerging from economic variables and pointing toward other dimensions' variables. The same procedure was followed to develop the social, environmental, and institutional sustainability dimensions.

Second, the feedback loops resulting from the relationships between resilience variables were identified in the CLD. It is important to highlight that the CLD in this research primarily revealed reinforcing loops that amplify the ongoing decline of system functioning, rather than balancing loops that would counteract these trends. The attention was focused on the reinforcing loops because of their significant potential to exacerbate problematic trends (Meadows 1999). Then the research team identified the delays in the feedback loops. To this end, they selected the resilience variables whose changes impact the state of the system with a time lag, generating delayed reactions.

Table 1. Resilience variables in the casual loop diagram.

Nº	Class[†]	Resilience variable[‡]	Indicator (unit)	Closeness to critical threshold	Threshold explanation	Delayed impact
1	**C**	**Reducing lamb meat consumption**	**Lamb meat consumption (kg/year/inhab)**	**At/beyond threshold**	**Lamb meat consumption has decreased 60% in 15 years and reached 1.09 kg/inhabitant/year in Spanish households in 2021 (MAPA 2022).**	**Delay**
2	**C**	**Increasing feeding costs**	**Feeding costs (€/year)**	**At/beyond threshold**	**Feeding costs' critical threshold is around 30 €/head (Paas et al. 2021a).**	
3	C	Increasing wildlife attacks	Wildlife attacks (attacks/year)	Not close		Delay
4	**C**	**Lack of workforce**	**Available workforce (annual work unit [AWU]/farm)**	**At/beyond threshold**	**The AWU critical threshold is 1.9 AWU per farm (Paas et al. 2021a).**	**Delay**
5	F	Economic viability	Gross margin (€/year)	Somewhat close		
6	**F**	**Food production**	**Number of sheep (number/year)**	**At/beyond threshold**	**It has decreased 62% in 20 years and reached 347,800 sheep in Huesca in 2022 (Government of Aragón 2023a).**	
7	**F**	**Quality of life**	**Number of farms (number/year)**	**At/beyond threshold**	**It has decreased 70% in 20 years and reached 863 farms in Huesca in 2022 (Government of Aragón 2023a).**	**Delay**
8	F	Natural resources conservation	Pastures grazed (ha/year)	Not defined		Delay
9	A	Production coupled with local and natural resources	Available pastures (ha)	Somewhat close		Delay
10	**A**	**Diverse policies**	**Subsidies-CAP Pillar 1 (€/year), rural development programs (RDP)-CAP Pillar 2 (€/year), environmental, health, and urban legislation (No. of enabling policies)**	**At/beyond threshold**	**The critical threshold for subsidies is defined at around 31 € per sheep (Paas et al. 2021a). Environmental, health, and urban legislation hinders extensive systems' resilience (Soriano et al. 2022).**	**Delay**
11	A	Socially self-organized	Farmers' cooperation (Index)	Not close		Delay
12	A	Support of rural life	Region attractiveness (Index)	Close		Delay
13	A	Infrastructure of innovation	Farm technology investment (€/year)	Close		Delay
14	**A**	**Earnings[§]**	**Financial reserves (€)**	**At/beyond threshold**	**Because of low gross margin of 25–30 €/head (Paas et al. 2021a), farmers do not count on financial reserves.**	**Delay**

[†] Challenges (C), functions (F), and attributes (A).
[‡] Resilience variables at or beyond the critical threshold are highlighted in bold.
[§] Reasonably profitable (Cabell and Oelofse 2012).

Third, the research team classified the strategies identified by the participants in the FoPIA-SURE Farm 2 workshop by inferring their scale as well as the vicious circles and resilience variables they were targeting. In the case of the resilience diverse policies attribute, the link between the strategies and the specific policies identified in the CLD (e.g., the CAP pillars) was also inferred.

RESULTS

Resilience variables in the causal loop diagram

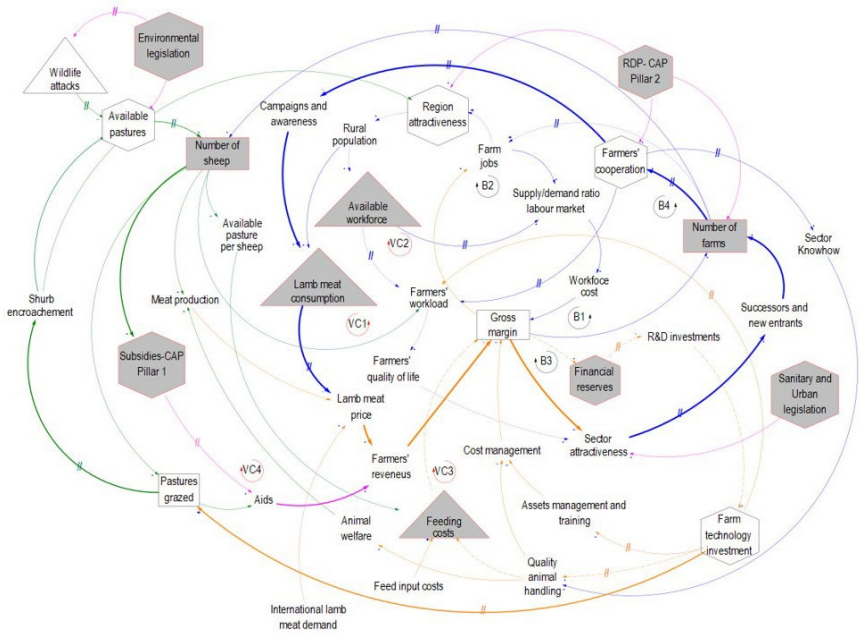
The CLD representing the dynamics of the extensive sheep farming system in Huesca included 14 resilience variables, with four challenges (C), four functions (F), and six resilience attributes (A; Table 1, Fig. 3). According to the participants in the FoPIA-SURE Farm 2 workshop, seven out of 14 resilience variables are at or beyond their critical threshold: three challenges (reducing lamb meat consumption, increasing feeding costs, and lack of workforce), two functions (food production and quality of life), and two resilience attributes (diverse policies and earnings). There are delays in the system's dynamics, triggered by challenges (e.g., reducing lamb meat consumption), system functions (e.g., natural resources conservation), and resilience attributes (e.g., production coupled with local and natural resources).

Feedback loops affecting resilience variables at or beyond the critical threshold

Four reinforcing loops acting as vicious circles, which are affecting the resilience variables at or beyond their critical threshold (Table 1), were identified in the extensive sheep system in Huesca (Fig. 3, Table 2). According to the participants, the vicious cycle VC1 shows that the challenge of reducing lamb meat consumption has been pressuring the sector with a delayed negative impact on the system's function of ensuring economic viability (gross margin). Reduced benefits have been making the sector unappealing for new generations and new entrants, which in turn have negatively impacted other systems' functions related to quality of life (number of farms) by limiting economic opportunities in the region. As the number of farms has decreased, farmers found it more difficult to cooperate, reducing the resilience attribute of being a socially self-organized system. Among others, constrained cooperation has reduced farmers' commitment to pursuing joint actions to promote lamb meat consumption, closing the loop with further declining lamb meat consumption.

Regarding the drivers, three vicious circles are triggered by challenges (VC1, VC2, and VC3) and one of them is triggered by a weak resilience attribute: diverse policies. The weak attribute of diverse policies implies that the farming system does not count on policies stimulating the three resilience capacities to avoid situations in which the system is locked into a robust but unsustainable situation (Appendix I). The participants in the workshop identified that existing policies do not adequately support resilience capacities. The CAP (Subsidies in Pillar 1 and Rural development program [RDP] in Pillar 2) does not support the system's robustness and adaptability as subsidies are not sufficient to ensure farms' income, sector sustainability, and region attractiveness. Regarding sanitary legislation (animal health and slaughter practices), many slaughterhouses in the region have closed in the past 15 years because they were not able not meet the national application of the EU regulation EC No. 852/2004, thus hindering the system's robustness capacity. Slaughterhouses have not been replaced by alternative initiatives (e.g., mobile slaughterhouses), leading to the closure of local distribution channels (butchers and other local retailers) and the increase in farmers' distribution costs. Environmental and urban legislation also limits a system's transformability capacity as it undermines farmers' capacity to invest in product transformation and restoration services. The resilience attribute of diverse policies is represented in the CLD by four variables related to the vicious circles identified: (i) the subsidies-CAP Pillar 1, which impact the

Fig. 3. Causal loop diagram representing dynamics in the extensive sheep farming system in Huesca (Spain).



economic viability function (gross margin) in VC4; (ii) RDP-CAP Pillar 2 affecting the support of the rural life attribute (region attractiveness) in VC2); (iii) environmental legislation affecting the production attribute coupled with local and natural resources (pastures grazed) in VC4; and (iv) urban and sanitary legislation affecting the sector's attractiveness (VC2).

The vicious circles show that challenges impact the functions provided by the extensive sheep farming system in Huesca. For example, reducing lamb meat consumption (C) and increasing feeding costs (C) affect economic viability (gross margin; F) in VC1 and VC3, respectively, and the lack of a skilled workforce (C) reduces the number of farms (F) in VC2. Moreover, the CLD (Fig. 3) shows that the system's functions are also influenced by resilience attributes. For example, the low level of infrastructure for innovation (farm technology investment; A) negatively impacts natural resources conservation (pastures grazed; F) in VC4. On the other hand, the low performance of the system's functions may also diminish its resilience attributes. For example, reduced economic viability (gross margin; F) negatively impacts social self-organization (farmers' cooperation; A) in VC1. Furthermore, functions can also mutually affect each other. For example, a reduced function of ensuring economic viability (gross margin), reduces other functions such as the provision of quality of life (number of farms) in VC1, food production (number of sheep), and conservation of natural resources (grazed pastures) in VC4. Finally, resilience attributes are also interrelated. This is the case, for example, of improved social self-organization (farmers' cooperation), which increases production coupled with local and natural resources (available pastures) in VC4. There are delays in the four vicious circles, caused by lamb meat consumption (C) in VC1, the workforce (available workforce; C) in VC2, food production (number of sheep; F) in VC4, quality of life (number of farms; F) in VC1 and VC2, and diverse policies (subsidies- CAP Pillar 1; A) in VC4.

The vicious circles also affect the four sustainability dimensions. VC1 shows the interrelations between economic and social dimensions and VC4 between economic, institutional, and environmental dimensions. VC2 and VC3 each run in a single dimension, although they are linked with the other vicious circles throughout the functions of contributing to quality of life (number of farms) in VC1-VC2 and ensuring economic viability (gross margin) in VC3-VC4. These links show the full interrelation between the sustainability dimensions in the dynamics of the system.

Finally, the system is balanced by four balancing loops that regulate the dynamics of the reinforcing loops across economic, social, and environmental sustainability dimensions (Table 2). The balancing loops limit economic benefits (B1), job creation (B2), technification benefits (B3), and natural resources availability (B4) through the impacts of prices, workforce cost, assets management and training costs, and pasture land availability, respectively. There are also delays in the balancing loops derived from quality of life (number of farms; F) in B1 and B4, and earnings (financial reserves; A) and innovation infrastructure (farm technology investments; A) in B3. There are no delays in B2.

Strategies to turn vicious into virtuous circles

Most of the strategies (15/21) identified by the participants in the FoPIA-SURE Farm 2 workshop designed to reach the desired alternative system or systems, may improve the state of the resilience variables at or beyond critical threshold levels (columns 1 and 2, Table 3). Participants proposed a set of strategies to meet the challenges of resilience variables at or beyond their critical threshold. For example, they suggested reinforcing product origin to remedy decreasing lamb meat consumption and to promote generational renewal, which would ease the dwindling workforce. They also suggested developing financial instruments to hedge

Table 2. Feedback loops in the extensive sheep farming system in Huesca (Spain). CLD = causal loop diagram.

Vicious circles	Resilience indicators[†]	Sustainability dimension			
		Eco.	Soc.	Env.	Inst.
VC1- Consumption (major thickness line in CLD)	⇓**Lamb meat consumption (C)** //→⇓ Lamb meat price →⇓ Farmers' revenues →⇓ Gross margin (F) →⇓ Sector attractiveness →⇓ Successors and new entrants →⇓ **Number of farms (F)** //→⇓ Farmers' cooperation (R) //→ ⇓ Campaigns and awareness →⇓ **Lamb meat consumption (C)** (interrelated with VC3 and VC4 through gross margin).	X	X		
VC2- Available workforce (dotted lines in CLD)	⇓ **Available workforce (C)** //→⇑ Farmers' workload→⇓ Farmers' quality of life →⇓ Sector attractiveness →⇓ Successors and new entrants →⇓ **Number of farms (F)** //→⇓ Farm jobs →⇓ Region attractiveness (A) //→⇓ Rural population →⇓ **Available workforce (C)** (interrelated with VC1 through the number of farms).		X		
VC3- Feeding costs (dashed lines in CLD)	⇑ **Feeding costs (C)** →⇓ Gross margin (F) →⇓ **Financial reserves (A)** //→⇓ R&D Investments →⇓ Farm technology investment (A) //→⇓ Quality animal handling →⇑ **Feeding costs (C)** (interrelated with VC1 through gross margin).	X			
VC4- Policy diversity (medium thick lines in CLD)	⇓ **Subsidies-CAP Pillar 1 (A)** //→⇓ Aids→⇓ Farmers' revenues →⇓ Gross margin (F)→⇓ **Financial reserves (A)** //→⇓ R&D Investments→⇓ Farm technology investment (A) //→⇓ Pastures grazed (F) //→⇑ Shrub encroachment →⇓ Available pastures (A) //→⇓ **Number of sheep (F)**→⇓ **Subsidies-CAP Pillar 1 (A)** (interrelated with VC1 through gross margin)	X		X	X
B1- Limited economic benefits	⇑ Gross margin (F) →⇑ **Number of farms (F)** //→⇑ **Number of sheep** →⇑ Food production (F) →⇓ Lamb meat prices →⇓ Gross margin (F) (interrelated with VC1,2,3,4).	X			
B2- Limited job creation	→⇑ Farm jobs→⇑ Supply/Demand ratio labour maker →⇑ Workforce costs → ⇓ Gross margin (F)→⇓ Farm jobs (interrelated with VC1,2,3,4).		X		
B3- Limited technification benefits	→⇑ Gross margin (F) → ⇑ **Financial reserves (A)** //→⇑ R&D Investments → ⇑ Farm technology investment (A) //→ ⇑ Assets management and training → ⇑ Cost management → ⇓ Gross margin (F) (interrelated with VC1,2,3,4).	X			
B4- Limited natural resources	⇑ **Number of farms (F)** //→⇑ **Number of sheep** →⇓ Land available per sheep →⇑ **Feeding costs (C)** →⇓ Gross margin (F) → ⇓ **Number of farms (F)** (interrelated with VC1,2,3,4).			X	

[†] VC: Reinforcing loops functioning as vicious circles; B: balancing loops; in brackets the resilience variables' classification: C (challenge), F (function), A (attribute); in bold resilience variables at or beyond the critical threshold; //→: Delays; ⇑ resilience variable increases, ⇓ resilience variable decreases. Columns: Eco. (economic dimension), Soc. (social dimension), Env. (environmental dimension), and Inst. (institutional dimension).

volatility as a solution to increasing feeding costs. This set of strategies to deal with challenges is defined at the regional (e.g., create shepherding schools) and national levels (e.g., promote consumption of meat from local breeds outside the region; column 3, Table 3).

Almost half of the strategies proposed by participants (9/21) are tailored to improve the diverse policies resilience attribute, which is also at or beyond its critical threshold. The proposed strategies are related to policies such as the CAP (e.g., remuneration for provisioning public goods), sanitary legislation (e.g., adapt legislation to the sanitary conditions of the extensive farming sector), and urban legislation (e.g., develop new urban legislation in rural areas that considers coexistence with the livestock sector) as well as bureaucracy (e.g., use technology for real-time communication). The scale of this set of strategies ranges from both the regional (e.g., train local authority staff in regional specificities) and national levels (e.g., develop legislation tailored to environmental management), as well as to the European level (e.g., reduce excessive and specific regulations).

The participants also identified strategies tailored to improving resilience attributes (i.e., production coupled with local and natural resources and infrastructure for innovation) and functions (i.e., economic viability and natural resources conservation), which are not at or beyond the critical threshold. In this case, the strategies range from the local (e.g., open local slaughterhouses to reduce farmers' cost) to the European level (e.g., research on more prolific and productive breeds to improve the economic viability of farms).

There are resilience variables that are not directly addressed by the set of strategies mentioned by the participants. Some of them are resilience variables at or beyond their critical threshold such as the earnings resilience attribute (financial reserves), the food production functions (number of sheep), and quality of life (number of farms). The rest of the resilience variables that are not directly addressed by the strategies identified by the participants are the socially self-organized and support of rural life attributes.

The strategies identified by the participants may contribute to reversing all the vicious circles identified (columns 4, 5, 6, Table 3) and to shifting the trends away from collapse. The strategies are mainly oriented to VC3 and VC4 (Table 3). For example, the participants identified strategies focused on reinforcing farm technology (infrastructure for innovation attribute), such as investing in farm efficiency, animal tracking, and grazed pasture monitoring technology. By implementing these strategies, farmers in the sheep system will be able to reduce feeding costs and improve economic viability (gross margin; VC3). Furthermore, increased farm technology will foster natural resources conservation (grazed pastures), which in turn will reduce shrub encroachment and reinforce the resilience attribute of having production combined with local and natural resources (available pastures).

DISCUSSION

In this article we have applied participatory methods to investigate the dynamics of an extensive livestock system through the lens of resilience and sustainability. This analysis has allowed us to map out the relationship between resilience variables and to understand specific system dynamics. Many studies on the resilience and sustainability of agriculture use a static approach (Slijper et al. 2022, Prat-Benhamou et al. 2024). Others, in an attempt to generalize knowledge on complex systems, resort to simple rules of thumb or heuristics (Bennett et al. 2005, Biggs et

Table 3. Strategies favoring a desired alternative extensive sheep farming system.

Strategy	Resilience variable	Scale	VC1	VC2	VC3	VC4
Promote consumption of meat from local breeds outside the region	**Lamb meat consumption (C)**	National	**X**			
Reinforce product origin and certification	**Lamb meat consumption (C)**	National	**X**			
Promote generational renewal (early retirement, access to land, etc.)	**Lack of workforce (C)**	Regional		**X**		
Create shepherding schools	**Lack of workforce (C)**	Regional		**X**		
Develop financial products to cover volatile market input prices	**Feeding costs (C)**	National			**X**	**X**
Facilitate access to pastures and stubble fields	**Diverse policies (A)**/ Production coupled with local and natural resources (A)	Regional				**X**
Remunerate the sector for contribution to public goods	**Diverse policies (A)**/Natural resources conservation (F)	Regional/ National/ European				**X**
Develop legislation tailored to environmental management	**Diverse policies (A)**	Regional/ National/ European				**X**
Open local slaughterhouses	**Diverse policies (A)**/Economic viability (F)	Local/Regional				**X**
Adapt legislation to the sanitary conditions of the extensive sector	**Diverse policies (A)**	Regional/ National				**X**
Develop new urban legislation in rural areas considering coexistence with the livestock sector	**Diverse policies (A)**	Regional/ National				**X**
Use technology for real-time communication with local authorities	**Diverse policies (A)**	Regional/National				**X**
Train local authority staff in regional specificities	**Diverse policies (A)**	Regional				**X**
Reduce bureaucracy and excessive and specific regulations	**Diverse policies (A)**	Regional /National/ European				**X**
Invest in technology to improve efficiency (electronic readers, blood tests, etc.)	Infrastructure for innovation (A) / Economic viability (F)	Regional/National			**X**	**X**
Investment in technology for animal tracking (GPS, mobile phone, etc.)	Infrastructure for innovation (A)/ Production combined with local and natural resources (A)/Wildlife attacks (C)	National			**X**	**X**
Investment in technology to control grazed pastures	Infrastructure for innovation (A)/ Natural resources conservation (A)	National			**X**	**X**
Farmer training in new technology	Infrastructure for innovation (A)	Regional			**X**	**X**
Research in sanitary control of the ovine sector (new vaccines, medications, etc.)	Economic viability (F)	National/European			**X**	**X**
Research in more prolific and productive breeds.	Economic viability (F)	National/European			**X**	**X**
Research in net methane emissions from ovine sector	Production coupled with local and natural resources (A)	National/European			**X**	**X**

The classification of the resilience variables is indicated in brackets: C (challenges), F (functions), and A (attributes). Resilience variables in bold are at or beyond the critical threshold. The vicious circles (VC1, VC2, VC3, and VC4) mainly targeted by strategy implementation are marked with an "X."

al. 2012, Cabell and Oelofse 2012, Tittonell 2020), without addressing the interactions between systems. This increases the probability of missing actionable knowledge that can be applied to improving the dynamics of the system (Bennett et al. 2005). The participatory qualitative approach employed also provides an accessible way to obtain a preliminary, and rather comprehensive, stakeholder-informed understanding of extensive livestock system dynamics.

Improved understanding of the relationships between resilience variables

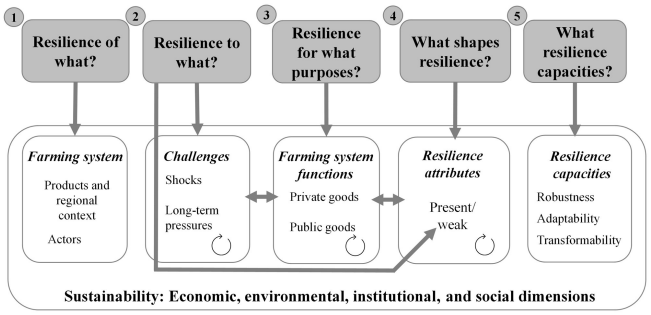
The qualitative system dynamics approach unveils the relationships between resilience variables. First, the ability of the system to provide functions is threatened not only by challenges (Darnhofer 2014, Meuwissen et al. 2019), such as increasing feeding costs or reducing lamb meat consumption, but also by weakly expressed resilience attributes, such as earnings (financial reserves) and diverse policies (CAP, environmental, sanitary, and urban legislation). Walker and Salt (2012) found that the dynamics of change in systems are mainly influenced by the lack of forms of capital, i.e., system resources, in addition to external disturbances. Regarding the weak attribute of diverse policies (the lack of policies supporting the system's resilience capacities, robustness, adaptability, and transformability), Soriano et al. (2022) found that policies contribute very little to the resilience of the extensive sheep farming system in Huesca because policy instruments have been mainly tailored to support farmers' income, instead of strengthening other resilience variables such as the nature conservation function (pastures grazed) or the resilience attribute of supporting rural life (region attractiveness). Tenza et al. (2017) established that external (exogenous) and internal (endogenous) drivers threaten farming systems' resilience. By applying a qualitative system dynamics approach, these authors found that a social-ecological system's tendency to collapse (an oasis in Mexico) was triggered by exogenous factors (e.g., development of modern agriculture in nearby valleys) and maintained by the endogenous structure (e.g., services and infrastructure).

Second, the results also indicate that the system's functions are interrelated and influence each other. For example, the diminished provision of private goods, such as the provision of economic viability (gross margin), has discouraged farmers from remaining in the sector, leading to a reduction in the provision of public goods such as quality of life (number of farms) and natural resources conservation (pastures grazed). In this regard, previous studies have shown that the lack of adequate economic incentives, such as market prices, discourage agricultural landowners from producing ecosystem services (Kroeger and Casey 2007). Additionally, farmers with secured income over an extended period of time are able to gain further awareness and knowledge of management for multiple ecosystem services (Smith and Sullivan 2014).

Third, challenges and resilience attributes are also interrelated. Regarding the former, Komarek et al. (2020) concluded that the agricultural sector is confronted with multiple risks that influence each other and interact. Girdžiūtė (2012) explained that production risks are related to personal and economic risks, which in turn arise from political risks and regulations, which also affect credit risks. In this regard, although the literature addressing synergies and trade-offs between resilience attributes is scarce,

previous studies have investigated the relationships between the resilience attributes identified in this research: (i) The positive relationship between the socially self-organized attribute (farmers' cooperation) and production coupled with local and natural resources (available pastures) was analyzed by Brekke et al. (2007). They concluded that farmers' cooperation stabilizes the ecosystem and avoids overgrazing under different climate variations. (ii) The positive relationship between the earnings attribute (financial reserves) and infrastructure for innovation (farm technology investments) was assessed by Tey and Brindal (2012). They found that farm capital (including the proxy variables farm sales, production value, farm income, and debt-to-assets ratio) is a significant factor influencing the adoption of precision agricultural technology. In this way, a farmer who has greater capital will have a greater financial capacity to innovate (Edwards-Jones 2006). The in-depth understanding of the relationships between resilience variables allows us to improve the starting theoretical framework (Fig. 1) by adding that challenges and weak attributes threaten farming systems, and that challenges, functions, and attributes are interrelated (Fig. 4).

Fig. 4. Improved farming system resilience and sustainability assessment framework,



Feedback loops that lead the system close to collapse

We identified four reinforcing loops, three of them delayed, functioning as vicious circles in the extensive sheep farming system, which explain the trend of the system toward collapse. Some of the resilience variables at or beyond the critical threshold (meat consumption, lack of workforce, quality of life, diverse policies, and financial reserves) are embedded in the delayed vicious circles, indicating that it has taken them a long time to reach the critical threshold level. This deterioration of the resilience variables can be explained by the fact that it has not been perceived or there have not been suitable strategies to stop or reverse its trend. The participants in the workshop explained that the extensive sheep production system has not been of interest to private (value chain actors) and public (policy makers) actors. Lamb meat is considered particular in taste, difficult to cook, and expensive, conditions that make it unsuitable for regular consumption (Martin-Collado et al. 2019) and hence not a core product for distribution and retailers. The low contribution of sheep farming to the agricultural production value added at the national level, which reached 2% in 2022 (MAPA 2023c), may also explain why policy makers pay little attention to this sector. Delays can elucidate why previous efforts made in the sector have failed (Sterman 2000).

Furthermore, vicious circles are interrelated. In addition to economic viability (gross margin) as the main system function variable pivoting the interaction of thresholds (Paas et al. 2021b), the present study suggests that the quality of life function (number of farms) and the earnings attribute (financial reserves) also link the existing vicious circles in the system. Regarding the former, the reduced number of farms may lead to reducing farmers' cooperation because they feel isolated (VC1) and to reducing labor opportunities and hence region attractiveness and rural population (VC2). If these variables fall below their critical threshold, system behavior will be nearly irreversible, given that the rural population will emigrate, and the rural infrastructure will no longer be maintained. The latter shows that diminished financial reserves reduce farm technology investment targeted at improving herd management, which in turn reduces feeding costs (VC3), facilitates grazing management, and increases pasture availability, thus preventing shrub encroachment (VC4).

This study focused on reinforcing loops that are identified as places in the system with high leverage potential (Meadows 1999). This is also a logical choice for the extensive sheep system in Huesca, with the ongoing decline of the system's functioning, hinting at dominant vicious circles. Even so, balancing loops have been identified that regulate the dynamics of the system, specifically vicious circles. Once vicious circles are turned into virtuous circles, balancing loops will increase in strength and eventually dominate the system's behavior. From a positive point of view, balancing loops can provide stability to the system once desired sustainability levels are reached. However, the stabilizing function of balancing loops can also resist further improvement before these levels are reached, thus hindering a full sustainability transition (de Gooyert et al. 2016). Once vicious circles are being treated, researchers and stakeholders should pay attention to balancing loops to be able to guide the transition process.

Integrated assessment of resilience and sustainability

We found that resilience variables' vicious circles ran across sustainability dimensions, revealing the interactions between resilience and sustainability. These interrelations reinforce the idea that resilience and sustainability are two interrelated objectives (Saunders and Becker 2015). In our case study, enhancing resilience by improving the resilience attributes of economic viability (gross margin), quality of life (number of farms), and earnings (financial reserves) results in long-term impacts, including an increase in the attractiveness of the sector and rural areas, and the conservation of natural resources for newcomers and existing populations. The dynamics in the extensive sheep farming system show several resilience variables: economic (e.g., feeding costs), social (e.g., lamb meat consumption), environmental (e.g., natural resources conservation), and institutional (e.g., diverse policies); this indicates that moving toward a sustainable system requires a system that is already resilient. The interrelation between resilience and sustainability shows the need for an integrated approach. Trade-offs between strategies addressing resilience and sustainability will be less likely to appear once the interrelations between these two aims have been identified (Saunders and Becker 2015).

The results of the present study also show that sustainability dimensions are interrelated. Previous studies (Hansmann et al. 2012, Galdeano-Gómez et al. 2017) found synergies across

sustainability dimensions in the agricultural sector. For example, improving nature conservation (environmental dimension) benefits protection of the population's health and safety (social dimension). Innovation and modernization (economic dimension) can generate social and economic benefits and promote sustainable use of natural resources (environmental dimension). Building social and human capital and better natural resources management can increase income (economic dimension). Trade-offs between (inter- and intra-) sustainability dimensions in social-ecological systems could also exist. For example, the reduction of cattle herds to control the degradation of vegetation negatively impacts the endangered population of scavengers (Banos-González et al. 2015).

Strategies to turn vicious into virtuous circles

The participants in the FoPIA-SURE Farm 2 workshop identified a set of strategies that target the resilient variables at or beyond the critical threshold and thus involved in vicious circles (Table 3), which could reverse the trend of the system and turn it toward collapse. Although the participants proposed a number of strategies to meet challenges (e.g., reinforcing the labeling of a product's origin and quality certification to promote lamb meat consumption), because it has traditionally been studied in the risk management literature (Bardají et al. 2016), most of their suggestions aimed at reinforcing resilience attributes, i.e., diverse policies and infrastructure for innovation. The strategies to reinforce the attribute of diverse policies aim at paying for the provision of public goods and adapting policies that regulate pasture accessibility, environmental protection, and sanitary conditions to extensive livestock farming characteristics. These strategies may impact almost all the vicious circles through the VC4 as well as the different sustainability domains, contributing to preventing the system's collapse. The FoPIA-SURE Farm 2 workshop took place before the enforcement of the new CAP 2023–2027 measure in which eco-schemes were defined to support the provision of public goods. In Spain, the CAP strategic plan defines a specific practice (extensive grazing-P1) to support extensive livestock farmers with payments that range between 40.96 €/ha (Mediterranean pastures) and 62.16 €/ha (wet pastures; MAPA 2023d). According to the VC4, this is expected to increase farmers' income, financial reserves, and investment in new technologies (e.g., animal geo-localization and digitalization) to reinforce their function of environmental conservation by increasing the number of hectares grazed.

The strategies to reinforce the structure for the innovation attribute, proposed by the participants in the FoPIA-SURE Farm 2 workshop, encompass boosting research, innovation, and training (Table 3). These strategies will foster farm efficiency and productivity as well as improve pasture management in ways that reduce management and feeding costs and increase gross margins. Candel et al. (2020) found that closing the gap between innovation (e.g., in monitoring the use of pastures) and practice would support systems' resilience by supporting its adaptability capacity.

Although not identified by the participants in the FoPIA-SURE Farm 2 workshop, it would also be advisable to define a set of strategies tailored to improving the earnings attribute (financial reserves) and the quality of life function (number of farms), because they are variables at or beyond their threshold embedded in the vicious circles. Because of the current low number of farms, common initiatives that allow financing farms are difficult to implement, such as joint investments or mutual funds developed under the operational programs (EC Regulation 2017/89). In Spain, so far, operational programs are implemented only in the fruit and vegetables sector (MAPA 2023d). To increase the number of farms, the RDP-CAP Pillar 2 plays an important role: it is one of the main policy instruments for rural dynamization, supporting rural entrepreneurship and the region's attractiveness. The RDP 2014–2020 in Aragón allocated 8% of the budget to support the installation of young farmers and investments in fixed assets (Government of Aragón 2023b). RDPs have the potential to not only improve the region's social fabric, but also to support traditional practices and agri-environmental measures driven by cooperation within the local community. Cooperation between the actors in a farming system is claimed by other authors to improve the system's resilience. Moving from farmer-centered strategies to multi-actor strategies may enhance resilience (Meuwissen et al. 2020), as every actor in a farming system may improve the resilience attributes and capacities in different ways (Soriano et al. 2023).

Given that there are multiple vicious circles interacting and reinforcing each other, it is unlikely that one strategy is sufficient to shift loop direction and turn vicious circles into virtuous ones. This result is in line with Reidsma et al. (2023), who found that strategies in multiple domains should be implemented simultaneously to improve the system's resilience and sustainability. Restoring resilience variables that are at or beyond the critical threshold with a delayed impact on the system's dynamics (i.e., lamb meat consumption, lack of workforce, quality of life, diverse policies, and earnings) will require sustained strategies (Paas et al. 2021b), such as raising awareness and expanding scientific evidence to promote lamb meat consumption (Scholl et al. 2010); promoting investment in agricultural education, and vocational training courses to build a skilled human capital workforce (Ryan 2023); defining instruments (e.g., Income Stabilization Tool and insurances) to enhance incomes and reduce income variability (EC 2018); as well as supporting research and innovation programs, advisory systems, and rural infrastructure to trigger farm productivity (EC 2019).

The scales of the strategies should also be taken into consideration. Based on the strategies informed by participants in the FoPIA-SURE Farm 2 workshop, a combination of strategies at different scales, from the local (e.g., open local slaughterhouses) to the European level (promote research in sanitary control of the ovine sector), is needed to move the farming system away from collapse and toward a more resilient and sustainable system.

Similar to other extensive livestock farming systems in the EU, the case study presented herein has brought to light a variety of strategies to improve the resilience and sustainability of such systems, and it contributes to other research aimed at ensuring the agroecological transition of the European livestock sector (Peyraud and Macleod 2020).

CONCLUSION

We have analyzed the dynamics of the extensive sheep farming system in Huesca, Aragón (Spain), a system that has shown a low resilience capacity and is close to collapse. A qualitative system dynamics model in the form of a CLD has been developed to investigate complex system dynamics through the lens of resilience and sustainability thinking.

Resilience variables at or beyond their critical threshold in extensive sheep farming in Huesca are embedded in vicious circles, explaining the system's trends toward collapse. Relationships between resilience variables in the vicious circles reveal that when addressing the system's resilience and sustainability, it is worth considering that the system may be threatened not only by challenges (lowering lamb meat consumption, lack of workforce, increasing costs), but also by weak attributes (lack of diverse policies) and already diminished functions (reducing number of farms).

Examining delays showed that resilience is a system's capacity to meet all types of challenges, it is built over a long period of time, and poor resilience cannot return to full capacity over the short term. Furthermore, the link between any vicious circles in the system reveals the complexity of these interconnected resilience and sustainability dimensions. Based on these results, when designing pathways for enabling the resilience and sustainability of extensive farming systems in Europe, it is advisable to consider that a broad range of interventions are needed in the long run to deal with challenges, weak attributes and diminished functions pertaining to the economic, social, institutional and environmental domains. This multi-target approach requires, for example, reinforcing the coordination between different policies. The CAP subsidies cannot enhance extensive livestock systems' resilience and sustainability if it is not adequately coordinated with other policies influencing the system, i.e., environmental, sanitary, urban, labor, consumption and innovation policies.

These results should be considered with caution. Although the proposed participatory approach is supported by a theoretical framework, a literature review, and scientific evidence, the results can be biased by subjectivity and arbitrariness inherent in our participatory approach. This approach could be enriched by building a quantitative dynamic simulation model, as a subsequent step to test it. Finally, the methodology proposed does not address the potential trade-offs between strategies addressing resilience and sustainability at multiple scales. Complementary methods are hence necessary.

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We would like to dedicate the paper to the memory of Pytrik Reidsma who passed away in June 2024. We want to thank her for her positive attitude in supporting the team and recurrent reminders to be precise and consistent in applying systems thinking and its terminology. We are proud of her passion for her work and getting a greener world with respect for nature, sustainability, and equality.

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Data Availability:

The data that support the findings of this study are available on request from the corresponding author, BS.

LITERATURE CITED

Anderies, J. M., C. Folke, B. Walker, and E. Ostrom. 2013. Aligning key concepts for global change policy: robustness, resilience, and sustainability. Ecology and Society 18(2):8. https://doi.org/10.5751/ES-05178-180208

Bala, K. B., F. M. Arshad, and K. M. Noh. 2017. System dynamics: modelling and simulation. Springer Science+Business Media, Singapore. https://doi.org/10.1007/978-981-10-2045-2

Banos-González, I., J. Martínez-Fernández, and M. A. Esteve-Selma. 2015. Dynamic integration of sustainability indicators in insular socio-ecological systems. Ecological Modelling 306:130-144. https://doi.org/10.1016/j.ecolmodel.2014.08.014

Bardají, I., A. Garrido, I. Blanco, A. Felis, and J. M Sumpsi. 2016. State of play of risk management tools implemented by member states during the period 2014-2020: National and European Frameworks. European Parliament, Brussels, Belgium.

Baur, I., and C. R. Binder. 2015. Modeling and assessing scenarios of common property pastures management in Switzerland. Ecological Economics 119:292-305. https://doi.org/10.1016/j.ecolecon.2015.09.019

Becking, J., B. Soriano, and I. Bardají. 2019. FoPIA-SURE-Farm case-study report Spain. In W. Paas, F. Accatino, F. Antonioli, F. Appel, I. Bardaji, I. Coopmans, P. Courtney, C. Gavrilescu, F. Heinrich, V. Krupin, G. Manevska-Tasevska, D. Neumeister, M. Peneva, J. Rommel, S. Severini, B. Soriano, M. Tudor, J. Urquhart, E. Wauters, K. Zawalinska, M. Meuwissen, and P. Reidsma. D5.2. Participatory impact assessment of sustainability and resilience of EU farming systems. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Belanche, A., D. Martín-Collado, G. Rose, and D. R. Yáñez-Ruiz. 2021. A multi-stakeholder participatory study identifies the priorities for the sustainability of the small ruminants farming sector in Europe. Animal 15(2):100131. https://doi.org/10.1016/j.animal.2020.100131

Bennett, E. M., G. S. Cumming, and G. D. Peterson. 2005. A systems model approach to determining resilience surrogates for case studies. Ecosystems 8:945-957. https://doi.org/10.1007/s10021-005-0141-3

Bernués, A., and A. Olaizola. 2012. La ganadería en los Pirineos: Evolución, condicionantes y oportunidades. Pages 29-67 in I. Lasagabaster, editor. Los Pirineos: geografía, turismo, agricultura, cooperación transfronteriza y derecho. Universidad del País Vasco, Leioa, Spain.

Bertolozzi-Caredio, D., I. Bardaji, I. Coopmans, B. Soriano, and A. Garrido. 2020. Key steps and dynamics of family farm succession in marginal extensive livestock farming. Journal of Rural Studies 76:131-141. https://doi.org/10.1016/j.jrurstud.2020.04.030

Biggs, R., M. Schlüter, D. Biggs, E. L. Bohensky, S. BurnSilver, G. Cundill, V. Dakos, T. Daw, L. S. Evans, K. Kotschy, et al. 2012. Toward principles for enhancing the resilience of ecosystem services. Annual Review of Environment and Resources 37 (1):421-448. https://doi.org/10.1146/annurev-environ-051211-123836

Bocchini, P., D. M. Frangopol, T. Ummenhofer, and T. Zinke. 2014. Resilience and sustainability of civil infrastructure: toward a unified approach. Journal of Infrastructure Systems 20 (2):4014004. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000177

Bosque, M., and V. P. Navarro. 2002. El proceso de desertización demográfica de la montaña pirenaica en el largo plazo. Ager: Revista de Estudios Sobre Despoblación y Desarrollo Rural, Aragón, Spain.

Brekke, K. A., B. Øksendal, and N. C. Stenseth. 2007. The effect of climate variations on the dynamics of pasture-livestock interactions under cooperative and non-cooperative management. Proceedings of the National Academy of Sciences 104 (37):14730-14734. https://doi.org/10.1073/pnas.0706553104

Brzezina, N., B. Kopainsky, and E. Mathijs. 2016. Can organic farming reduce vulnerabilities and enhance the resilience of the European food system? A critical assessment using system dynamics structural thinking tools. Sustainability 8(10):971. https://doi.org/10.3390/su8100971

Buitenhuis, Y., J. Candel, K. Termeer, P. Feindt, I. Coopmans, E. Lievens, E. Mathijs, E. Wauters, J. Urquhart, J. Black, et al. 2019. Policy bottom-up analysis. Five case study reports with the results of the assessments in the five regional case study areas. SURE-Farm Project, Deliverable 4.3.

Cabell, J. F., and M. Oelofse. 2012. An indicator framework for assessing agroecosystem resilience. Ecology and Society 17(1):18. https://doi.org/10.5751/ES-04666-170118

Candel, J. J. L., P. H. Feindt, C. J. A. M. Termeer, E. Mathijs, Y. Buitenhuis, M. Moeyersons, E. Lievens, J. Black, J. Urquhart, M. Vigani, et al. 2020. Deliverable D 4.5. Policy recommendations for strengthening the Common Agricultural Policy's resilience impacts. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Casasús, I., A. Bernués, A. Sanz, D. Villalba, J. L. Riedel, and R. Revilla. 2007. Vegetation dynamics in Mediterranean forest pastures as affected by beef cattle grazing. Agriculture, Ecosystems and Environment 121(4):365-370. https://doi.org/10.1016/j.agee.2006.11.012

Cumming, G. S., and G. D. Peterson. 2017. Unifying research on social-ecological resilience and collapse. Trends in Ecology & Evolution 32(9):695-713. https://doi.org/10.1016/j.tree.2017.06.014

Darnhofer, I. 2014. Resilience and why it matters for farm management. European Review of Agricultural Economics 41 (3):461-484. https://doi.org/10.1093/erae/jbu012

Darnhofer, I., J. Fairweather, and H. Moller. 2010. Assessing a farm's sustainability: insights from resilience thinking. International Journal of Agricultural Sustainability 8(3):186-198. https://doi.org/10.3763/ijas.2010.0480

Datola, G., M. Bottero, E. de Angelis, and F. Romagnoli. 2022. Operationalising resilience: a methodological framework for assessing urban resilience through system dynamics model. Ecological Modelling 465:109851. https://doi.org/10.1016/j.ecolmodel.2021.109851

de Gooyert, V., E. Rouwette, H. van Kranenburg, E. Freeman, and H. van Breen. 2016. Sustainability transition dynamics: towards overcoming policy resistance. Technological Forecasting and Social Change 111:135-145. https://doi.org/10.1016/j.techfore.2016.06.019

Edwards-Jones, G. 2006. Modelling farmer decision-making: concepts, progress and challenges. Animal Science 82(6):783-790. https://doi.org/10.1017/ASC2006112

European Commission (EC). 2018. Ensuring viable farm income. Brief No 1. CAP Specific Objectives. EC, Brussels, Belgium.

European Commission (EC). 2019. Increasing competitiveness: the role of productivity. EC, Brussels, Belgium.

European Commission (EC). 2020. Farm to fork strategy, for a fair, healthy and environmentally-friendly food system. EC, Brussels, Belgium.

Fiksel, J. 2006. Sustainability and resilience: toward a systems approach. Sustainability: Science, Practice and Policy 2(2):14-21 https://doi.org/10.1080/15487733.2006.11907980

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockström. 2010. Resilience thinking: integrating resilience, adaptability and transformability. Ecology and Society 15(4):20. https://doi.org/10.5751/ES-03610-150420

Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30:441-473. https://doi.org/10.1146/annurev.energy.30.050504.144511

Forrester, J. W. 1993. System dynamics and the lessons of 35 years. Pages 199-240 in K. B. De Greene, editor. A system-based approach to policymaking. Kluwer Academic, Dordrecht, The Netherlands. https://doi.org/10.1007/978-1-4615-3226-2_7

Galdeano-Gómez, E., J. A. Aznar-Sánchez, J. C. Pérez-Mesa, and L. Piedra-Muñoz. 2017. Exploring synergies among agricultural sustainability dimensions: an empirical study on farming system in Almería (Southeast Spain). Ecological Economics 140:99-109. https://doi.org/10.1016/j.ecolecon.2017.05.001

Gallopin, G. C. 2002. Planning for resilience: scenarios, surprises and branch points. Pages 361-392 in C. S. Holling and L. H. Gunderson, editors. Panarchy: understanding transformations in human and natural systems. Island, Washington, D.C., USA.

Girdžiūtė, L. 2012. Risks in agriculture and opportunities of their integrated evaluation. Procedia-Social and Behavioral Sciences 62:783-790. https://doi.org/10.1016/j.sbspro.2012.09.132

Government of Aragón. 2016. Ovine and caprine sector in aragón. evolution in the last 20 years (1996-2016). Government of Aragón, Zaragoza, Spain.

Government of Aragón. 2017. Special directive of demographic policy and against depopulation. Government of Aragón, Zaragoza, Spain.

Government of Aragón. 2023a. Agricultura, ganadería, selvicultura y pesca. Estadísticas de la ganadería. Government of Aragón, Zaragoza, Spain. https://servicios3.aragon.es/iaeaxi/menu.do?type=pcaxis&path=/08/01/08&file=pcaxis

Government of Aragón. 2023b. Measures of the Rural Development Program (2014-2020). Government of Aragón, Zaragoza, Spain. https://www.aragon.es/documents/20127/674325/PDR_2014_20_MEDIDAS_DOTACIONES_CUADRO.pdf/9f6a6033-9e7c-b3e8-1d69-c0b4f0ce4879

Groffman, P. M., J. S. Baron, T. Blett, A. J. Gold, I. Goodman, L. H. Gunderson, B. M. Levinson, M. A. Palmer, H. W. Paerl, G. D. Peterson, et al. 2006. Ecological thresholds: the key to successful environmental management or an important concept with no practical application? Ecosystems 9:1-13. https://doi.org/10.1007/s10021-003-0142-z

Hansmann, R., H. A. Mieg, and P. Frischknecht. 2012. Principal sustainability components: empirical analysis of synergies between the three pillars of sustainability. International Journal of Sustainable Development & World Ecology 19(5):451-459. https://doi.org/10.1080/13504509.2012.696220

Herman, A., M. Lähdesmäki, and M. Siltaoja. 2018. Placing resilience in context: investigating the changing experiences of Finnish organic farmers. Journal of Rural Studies 58:112-122. https://doi.org/10.1016/j.jrurstud.2017.12.029

Hernández-Mora, N., M. Gil, A. Garrido, and R. Rodríguez-Casado. 2012. La Sequía 2005-2008 en la cuenca del ebro: vulnerabilidad, impactos y medidas de gestión. UPM-CEIGRAM-Madrid, Spain.

Herrera, H., and B. Kopainsky. 2020. Using system dynamics to support a participatory assessment of resilience. Environment Systems and Decisions 40(3):342-355. https://doi.org/10.1007/s10669-020-09760-5

Hirsch, G. B., R. Levine, and R. L. Miller. 2007. Using system dynamics modeling to understand the impact of social change initiatives. American Journal of Community Psychology 39:239-253. https://doi.org/10.1007/s10464-007-9114-3

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4(5):390-405. https://doi.org/10.1007/s10021-001-0101-5

Inam, A., J. Adamowski, J. Halbe, and S. Prasher. 2015. Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: a case study in the Rechna Doab Watershed, Pakistan. Journal of Environmental Management 152:251-267. https://doi.org/10.1016/j.jenvman.2015.01.052

Kharrazi, A., P. Savaget, and S. Kudo. 2019. Resilience and sustainability. Pages 1-4 in W. Leal Filho, editor. Encyclopedia of sustainability in higher education. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-63951-2_92-1

Kinzig, A. P., P. Ryan, M. Etienne, H. Allison, T. Elmqvist, and B. H. Walker. 2006. Resilience and regime shifts: assessing cascading effects. Ecology and Society 11(1):20. https://doi.org/10.5751/ES-01678-110120

Komarek, A. M., A. De Pinto, and V. H. Smith. 2020. A review of types of risks in agriculture: what we know and what we need to know. Agricultural Systems 178:102738. https://doi.org/10.1016/j.agsy.2019.102738

Kroeger, T., and F. Casey. 2007. An assessment of market-based approaches to providing ecosystem services on agricultural lands. Ecological Economics 64(2):321-332. https://doi.org/10.1016/j.ecolecon.2007.07.021

Lane, D. C. 2001. Opportunities generated by the agency/structure debate and suggestions for clarifying the social theoretic position of system dynamics. System Dynamics Review 17(4):293-309. https://doi.org/10.1002/sdr.221

Li, F. J., S. C. Dong, and F. Li. 2012. A system dynamics model for analyzing the eco-agriculture system with policy recommendations. Ecological Modelling 227:34-45. https://doi.org/10.1016/j.ecolmodel.2011.12.005

Lie, H., and K. M. Rich. 2016. Modeling dynamic processes in smallholder dairy value chains in Nicaragua: a system dynamics approach. International Journal on Food System Dynamics 7 (4):328-340.

Lizarralde, G., K. Chmutina, L. Bosher, and A. Dainty. 2015. Sustainability and resilience in the built environment: the challenges of establishing a turquoise agenda in the UK. Sustainable Cities and Society 15:96-104. https://doi.org/10.1016/j.scs.2014.12.004

Maleksaeidi, H., and E. Karami. 2013. Social-ecological resilience and sustainable agriculture under water scarcity. Agroecology and Sustainable Food Systems 37(3):262-290. https://doi.org/10.1080/10440046.2012.746767

Marchese, D., E. Reynolds, M. E. Bates, H. Morgan, S. S. Clark, and I. Linkov. 2018. Resilience and sustainability: similarities and differences in environmental management applications. Science of the Total Environment 613-614:1275-1283. https://doi.org/10.1016/j.scitotenv.2017.09.086

Martin-Collado, D., C. Díaz Martín, M. Serrano, M. J. Carabaño, M. Ramón, and R. Zanoli. 2019. Sheep dairy and meat products: from urban consumers' perspective to industry innovations. CIHEAM 123:277-281.

Matthews, R., and P. Selman. 2006. Landscape as a focus for integrating human and environmental processes. Journal of Agricultural Economics 57(2):199-212. https://doi.org/10.1111/j.1477-9552.2006.00047.x

Meadows, D. 1999. Leverage points: places to intervene in a system. The Sustainability Institute.

Meuwissen, M. P. M., P. H. Feindt, P. Midmore, E. Waters, R. Finger, F. Appel, A. Spiegel, E. Mathijs, K. J. A. M Termeer, A. Balmann, et al. 2020. The struggle of farming-systems in Europe: looking for explanations through the lens of resilience. Eurochoices 19(2):4-11. https://doi.org/10.1111/1746-692X.12278

Meuwissen, M. P. M, P. H. Feindt, A. Spiegel, W. Paas, B. Soriano, E. Mathijs, A. Balmann, J. Urquhart, B. Kopainsky, A. Garrido, et al. 2022. SURE-Farm approach to assess the resilience of European farming systems. Pages 1-17 in M.

Meuwissen, P. Feindt, A. Garrido, E. Mathijs, B. Soriano, J. Urquhart, A. Spiegel, editors. Resilient and sustainable farming systems in europe: exploring diversity and pathways. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781-009093569.002

Meuwissen, M. P. M., P. H. Feindt, A. Spiegel, C. J. A. M. Termeer, E. Mathijs, Y. de Mey, R. Finger, A. Balmann, E. Wauters, J. Urquhart, et al. 2019. A framework to assess the resilience of farming systems. Agricultural Systems 176:102656. https://doi.org/10.1016/j.agsy.2019.102656

Milán, M. J., E. Arnalte, and G. Caja. 2003. Economic profitability and typology of Ripollesa breed sheep farms in Spain. Small Ruminant Research 49(1):97-105. https://doi.org/10.1016/S0921-4488(03)00058-0

Ministerio de Agricultura, Pesca y Alimentación (MAPA). 2022. Main figures of the ovine and caprine sector. Main economic indicators. MAPA, Madrid, Spain.

Ministerio de Agricultura, Pesca y Alimentación (MAPA). 2023a. Economic accounts of the agricultural sector in Spain. MAPA, Madrid, Spain. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/economia/cuentas-economicas-agricultura/

Ministerio de Agricultura, Pesca y Alimentación (MAPA). 2023b. Farm accountancy data network. MAPA, Madrid, Spain. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/economia/red-contable-recan/2015.aspx

Ministerio de Agricultura, Pesca y Alimentación (MAPA). 2023c. Resultados técnico-económicos de ovino de carne 2020. ECREA 2.0. Subdirección General de Análisis, Coordinación y Estadística. Subsecretaría. MAPA, Madrid, Spain.

Ministerio de Agricultura, Pesca y Alimentación (MAPA). 2023d. Spain's common agricultural policy strategic plan (2023–2027). Summary of the plan approved by the European Commission. MAPA, Madrid, Spain.

Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO). 2023. Legislation TED/339/2023, for the development of the list of wild species under special protection regime and the Spanish catalog of threatened species. Ministry for the Ecological Transition and the Demographic Challenge. MITECO, Madrid, Spain. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2023-8751

Navarro, V. P. 1992. La producción agraria en Aragón (1850-1935). Revista de Historia Económica / Journal of Iberian and Latin American Economic History 10(3):399-429. https://doi.org/10.1017/S021261090000358X

Ornai, A., G. Ne'eman, and T. Keasar. 2020. Management of forest fire buffer zones: implications for flowering plants and bees. Forest Ecology and Management 473:118310. https://doi.org/10.1016/j.foreco.2020.118310

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325 (5939):419-422. https://doi.org/10.1126/science.1172133

Paas, W., F. Accatino, F. Antonioli, F. Appel, I. Bardaji, I. Coopmans, P. Courtney, C. Gavrilescu, F. Heinrich, V., G. Manevska-Tasevska, et al. 2019. Deliverable D5.2 Participatory impact assessment of sustainability and resilience of EU farming systems. Sustainable and resilient EU farming systems (SURE-Farm) project report, EU Horizon 2020 Grant Agreement No. 727520.

Paas, W., F. Accatino, J. Bijttebier, J. E. Black, C. Gavrilescu, V. Krupin, G. Manevska-Tasevska, F. Ollendorf, M. Peneva, C. San Martin, et al. 2021b. Participatory assessment of critical thresholds for resilient and sustainable European farming systems. Journal of Rural Studies 88:214-226. https://doi.org/10.1016/j.jrurstud.2021.10.016

Paas, W., I. Coopmans, S. Severini, M. Van Ittersum, M. P. M. Meuwissen, and P. Reidsma. 2021c. Participatory assessment of sustainability and resilience of three specialized farming systems. Ecology and Society 26(2):2. https://doi.org/10.5751/ES-12200-260202

Paas, W., C. San Martín, B. Soriano, M. K. van Ittersum, M. P. M. Meuwissen, and P. Reidsma. 2021a. Assessing future sustainability and resilience of farming systems with a participatory method: a case study on extensive sheep farming in Huesca, Spain. Ecological Indicators 132:108236. https://doi.org/10.1016/j.ecolind.2021.108236

Pardos, L., M. T. Maza Rubio, and E. Fantova. 2008. The diversity of sheep production systems in Aragón (Spain): characterisation and typification of meat sheep farms. Spanish Journal of Agricultural Research 6(4):497-507. https://doi.org/10.5424/sjar/2008064-344

Peco, B., E. Navarro, C. P. Carmona, N. G. Medina, and M. J. Marques. 2017. Effects of grazing abandonment on soil multifunctionality: the role of plant functional traits. Agriculture, Ecosystems and Environment 249:215-225. https://doi.org/10.1016/j.agee.2017.08.013

Perrin, A., M. San Cristobal, R. Milestad, and G. Martin. 2020. Identification of resilience factors of organic dairy cattle farms. Agricultural Systems 183:102875. https://doi.org/10.1016/j.agsy.2020.102875

Peyraud, J., and M. Macleod. 2020. Study on future of EU livestock: how to contribute to a sustainable agricultural sector? Final Report. Directorate-General for Agriculture and Rural Development (European Commission), Brussels, Belgium.

Prat-Benhamou, A., A. Bernués, P. Gaspar, J. Lizarralde, J. M. Mancilla-Leytón, N. Mandaluniz, Y. Mena, B. Soriano, D. Ondé, and D. Martín-Collado. 2024. How do farm and farmer attributes explain perceived resilience? Agricultural Systems 219:104016. https://doi.org/10.1016/j.agsy.2024.104016

Reidsma, P., F. Accatino, F. Appel, C. Gavrilescu, V. Krupin, G. Manevska-Tasevska, M. P. M. Meuwissen, M. Peneva, S. Severini, B. Soriano, et al. 2023. Alternative systems and strategies to improve future sustainability and resilience of farming systems across Europe: from adaptation to transformation. Land Use Policy 134:106881. https://doi.org/10.1016/j.landusepol.2023.106881

Reidsma, P., M. P. M. Meuwissen, F. Accatino, F. Appel, I. Bardaji, I. Coopmans, C. Gavrilescu, F. Heinrich, V. Krupin, G. Manevska-Tasevska, et al. 2020. How do stakeholders perceive

the sustainability and resilience of EU farming systems? EuroChoices 19(2):18-27. https://doi.org/10.1111/1746-692X.12280

Richardson, G. P. 2011. Reflections on the foundations of system dynamics. System Dynamics Review 27(3):219-243. https://doi.org/10.1002/sdr.462

Richardson, G. P., and A. L. Pugh III. 1997. Introduction to system dynamics modeling with DYNAMO. Journal of the Operational Research Society 48(11):1146. https://doi.org/10.1057/palgrave.jors.2600961

Rodríguez-Ortega, T., E. Oteros-Rozas, R. Ripoll-Bosch, M. Tichit, B. Martín-López, and A. Bernués. 2014. Applying the ecosystem services framework to pasture-based livestock farming systems in Europe. Animal 8(8):1361-1372. https://doi.org/10.1017/S1751731114000421

Rounsevell, M. D. A., D. T. Robinson, and D. Murray-Rust. 2012. From actors to agents in socio-ecological systems models. Philosophical Transactions of the Royal Society B: Biological Sciences 367:259-269. https://doi.org/10.1098/rstb.2011.0187

Ruiz-Mirazo, J., and A. B. Robles. 2012. Impact of targeted sheep grazing on herbage and holm oak saplings in a silvo-pastoral wildfire prevention system in South-Eastern Spain. Agroforestry Systems 86(3):477-491. https://doi.org/10.1007/s10457-012-9510-z

Ryan, M. 2023. Labour and skills shortages in the agro-food sector. OECD Food, Agriculture and Fisheries Papers, No. 189. OECD, Paris, France.

Sanga, G. J., and E. D. Mungatana. 2016. Integrating ecology and economics in understanding responses in securing land-use externalities internalization in water catchments. Ecological Economics 121:28-39. https://doi.org/10.1016/j.ecolecon.2015.11.011

Saunders, W. S. A., and J. S. Becker. 2015. A discussion of resilience and sustainability: land use planning recovery from the Canterbury earthquake sequence, New Zealand. International Journal of Disaster Risk Reduction 14:73-81. https://doi.org/10.1016/j.ijdrr.2015.01.013

Scheffer, M., J. Bascompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. Van Nes, M. Rietkerk, and G. Sugihara. 2009. Early-warning signals for critical transitions. Nature 461(7260):53-59. https://doi.org/10.1038/nature08227

Scholl, G., F. Rubik, H. Kalimo, K. Biedenkopf, and Ó. Söebech. 2010. Policies to promote sustainable consumption: innovative approaches in Europe. Natural Resources Forum 34:39-50. https://doi.org/10.1111/j.1477-8947.2010.01294.x

Selman, P., and M. Knight. 2006. On the nature of virtuous change in cultural landscapes: exploring sustainability through qualitative models. Landscape Research 31(3):295-307. https://doi.org/10.1080/01426390600783517

Silva, V., F. X. Catry, P. M. Fernandes, F. C. Rego, P. Paes, L. Nunes, A. D. Caperta, C. Sérgio, and M. N. Bugalho. 2019. Effects of grazing on plant composition, conservation status and ecosystem services of Natura 2000 shrub-grassland habitat types. Biodiversity and Conservation 28(5):1205-1224. https://doi.org/10.1007/s10531-019-01718-7

Slijper, T., Y. de Mey, P. M. Poortvliet, and M. P. M. Meuwissen. 2022. Quantifying the resilience of European farms using FADN. European Review of Agricultural Economics 49(1):121-150. https://doi.org/10.1093/erae/jbab042

Smith, H. F., and C. A. Sullivan. 2014. Ecosystem services within agricultural landscapes -farmers' perceptions. Ecological Economics 98:72-80. https://doi.org/10.1016/j.ecolecon.2013.12.008

Soriano, B., A. Garrido, D. Bertolozzi-Caredio, F. Accatino, F. Antonioli, V. Krupin, M. P. M. Meuwissen, F. Ollendorf, J. Rommel, A. Spiegel, et al. 2023. Actors and their roles for improving resilience of farming systems in Europe. Journal of Rural Studies 98:134-146. https://doi.org/10.1016/j.jrurstud.2023.02.003

Soriano, B., A. Garrido, C. San Martín, D. Bertolozzi-Caredio, and I. Bardají. 2022. Opportunities to improve the resilience of extensive sheep farming in Huesca (Spain). Pages 156-170 in M. P. M. Meuwissen, P. H. Feindt, A. Garrido, E. Mathijs, B. Soriano, J. Urquhart, and A. Spiegel, editors. Resilient and sustainable farming systems in Europe: exploring diversity and pathways. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/9781009093569.010

Sterman, J. D. 2000. Business dynamics: systems thinking and modeling for a complex world. Irwin/McGraw-Hill, Boston, Massachusetts, USA.

Tenza, A., I. Pérez, J. Martínez-Fernández, and A. Giménez. 2017. Understanding the decline and resilience loss of a long-lived social-ecological system: insights from system dynamics. Ecology and Society 22(2):15. https://doi.org/10.5751/ES-09176-220215

Tey, Y. S., and M. Brindal. 2012. Factors influencing the adoption of precision agricultural technologies: a review for policy implications. Precision Agriculture 13:713-730. https://doi.org/10.1007/s11119-012-9273-6

Tidball, K. G., and M. E. Krasny, editors. 2014. Resilience and transformation in the red zone. Pages 25-43 in K. G. Tidball and M. E. Krasny, editors. Greening in the red zone: disaster, resilience and community greening. Springer, Dordrecht, The Netherlands. https://doi.org/10.1007/978-90-481-9947-1_2

Tip, T. 2011. Guidelines for drawing causal loop diagrams. Systems Thinker 22(1):5-7.

Tittonell, P. 2020. Assessing resilience and adaptability in agroecological transitions. Agricultural Systems 184:102862. https://doi.org/10.1016/j.agsy.2020.102862

Turner, N. C. 2004. Sustainable production of crops and pastures under drought in a Mediterranean environment. Annals of Applied Biology 144(2):139-147. https://doi.org/10.1111/j.1744-7348.2004.tb00327.x

Vennix, J. A. M. 1996. Group model building. Facilitating team learning using system dynamics. John Wiley & Sons, Chichester, UK.

Walker, B. H., L. H. Gunderson, A. P. Kinzig, C. Folke, S. R. Carpenter, and L. Schultz. 2006. A handful of heuristics and some propositions for understanding resilience. Ecology and Society 11(1):13. https://doi.org/10.5751/ES-01530-110113

Walker, B., and D. Salt. 2012. Resilience practice: building capacity to absorb disturbance and maintain function. Island, Washington D.C., USA. https://doi.org/10.5822/978-1-61091-231-0

Walters, J. P., D. W. Archer, G. F. Sassenrath, J. R. Hendrickson, J. D. Hanson, J. M. Halloran, P. Vadas, and V. J. Alarcon. 2016. Exploring agricultural production systems and their fundamental components with system dynamics modelling. Ecological Modelling 333:51-65. https://doi.org/10.1016/j.ecolmodel.2016.04.015

Wolstenholme, E. F. 1982. System dynamics in perspective. Journal of the Operational Research Society 33(6):547-556. https://doi.org/10.1057/jors.1982.117

Wolstenholme, E. F. 1999. Qualitative vs quantitative modelling: the evolving balance. Journal of the Operational Research Society 50:422-428. https://doi.org/10.1057/palgrave.jors.2600700

Xu, L., D. Marinova, and X. Guo. 2015. Resilience thinking: a renewed system approach for sustainability science. Sustainability Science 10:123-138. https://doi.org/10.1007/s11625-014-0274-4

Appendix 1: Resilience attributes

Resilience attributes	**Description**
1. Earnings[1]	Farmers and farm workers earn a livable wage while not depending heavily on subsidies.
2. Production coupled with local and natural capital	Soil fertility, water resources, and existing nature are maintained well.
3. Functional diversity	There is a high variety of inputs, outputs, income sources, and markets.
4. Response diversity	There is a high diversity of risk management strategies, e.g., different pest controls, weather insurance, flexible payment arrangements.
5. Exposed to disturbance	The amount of year-to-year economic, environmental, social, or institutional disturbance is small (well dosed) in order to timely adapt to a changing environment.
6. Spatial and temporal heterogeneity of farm types	There is a high diversity of farm types regarding economic size, intensity, orientation and degree of specialization.
7. Optimally redundant farms	Farmers can stop without endangering continuation of the system and new farmers can enter the system easily.
8. Supports for rural life	Rural life is supported by the presence of people from all generations, and supported by enough facilities in the nearby area (e.g., supermarkets, hospital).
9. Socially self-organized	Farmers are able to organize themselves into networks and institutions such as cooperatives, community associations, advisory networks, and clusters with the processing industry.
10. Appropriately connected with actors outside the farming system	Farmers and other actors in the system are able to reach out to policy makers, suppliers, and markets that operate at the national and EU levels.
11. Legislation coupled with local and natural capital	Norms, legislation, and regulatory frameworks are well adapted to the local conditions.
12. Infrastructure for innovation	Existing infrastructure facilitates knowledge and adoption of cutting-edge technologies (e.g., digital).
13. Diverse policies	Policies stimulate all three capacities of resilience, i.e. robustness, adaptability, transformability. Policies addressing all three resilience capacities avoid situations in which the system is permanently locked in a robust but unsustainable situation.
14. Ecologically self-regulated	Farms maintain plant cover and incorporate more perennials, provide habitat for predators, use ecosystem engineers, and align production with local ecological parameters.
15. Optimally redundant (crops)	Planting multiple varieties per crop rather than one; keeping equipment for various crops.
16. Optimally redundant (nutrients & water)	Obtaining nutrients and water from multiple sources.

Resilience attributes	Description
17. Optimally redundant (labor)	Labor comes from multiple sources.
18. Spatial and temporal heterogeneity (land use)	Diverse land use on the farm and across the landscape; mosaic pattern of managed and unmanaged land; diverse cultivation practices; crop rotations.
19. Globally autonomous and locally interdependent	Less reliance on commodity markets and reduced external inputs, more sales to local markets, reliance on local resources, existence of farmer cooperatives, close relationships between producers and consumers, shared resources such as equipment.
20. Reflective and shared learning	Extension and advisory services for farmers; collaboration between universities, research centers, and farmers; cooperation and knowledge sharing between farmers; record keeping; baseline knowledge about the state of the agroecosystem.
21. Honors legacy	Maintenance of old varieties and engagement of elders; incorporation of traditional cultivation techniques with modern knowledge.
22. Builds human capital	Investment in infrastructure and institutions for the education of children and adults; support for social events in farming communities; programs for preservation of local knowledge.

[1] Reasonably profitable (Cabell and Oelofse, 2012).

Source: Based on Reidsma et al. (2020) and Paas et al. (2021c).