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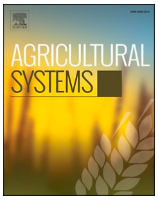

Research Paper

Explaining the decline of Mediterranean meat sheep farming through system dynamics modelling

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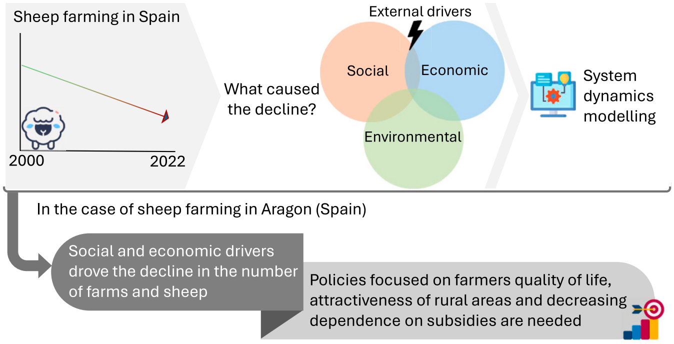
HIGHLIGHTS

- The decline of sheep farming (2000–2022) is simulated using a dynamic model.
- The system modelled includes social, economic and environmental drivers.
- Social and economic drivers drove the decline in the number of sheep and farms.
- Subsidies prevented the system from collapse but did not reverse its decline.
- Improving farmers quality of life and attractiveness of rural areas is key.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Farming systems are complex social-ecological systems in which social, economic, and ecological factors interact shaping their performance and evolution. Among different farming systems in Europe, sheep farming has experienced a marked and sustained decline over the past decades.
Objective: This paper uses a system dynamics model to investigate the decline of sheep farming systems in Mediterranean areas and to quantify the influence of different drivers on their dynamics.
Methods: The model SHEEPSES was developed to simulate the meat sheep farming system in Aragon (Spain) from 2000 to 2022. It incorporates the social, economic and environmental components that determine its functioning. First, we simulated the historical trends in the number of ewes, farms and net income per farmer. Second, we performed experimental simulations to understand what would have had happened if the effect of some drivers were removed.
Results and conclusions: Social and economic drivers drove the decline in the number of farms and sheep. This was caused by a lack of generational renewal, which was a consequence of poor quality of life and low attractiveness of rural areas. The system would have collapsed without the subsidies of the Common Agricultural Policy.

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However, our results suggest that policies have proven insufficient to reverse the declining trend in sheep and farm numbers. Policies focused on farmers quality of life, attractiveness of rural areas and decreasing dependence on subsidies would be needed to improve the system resilience in the long term.

Significance: SHEEPSES was helpful to understand past dynamics and could be a tool to support policy design aiming at slowing the decline of the system.

1. Introduction

Farming systems are complex social-ecological systems in which social, economic, institutional, and ecological factors interact across multiple spatial and temporal scales, shaping their performance and long-term evolution (Morales-Reyes et al., 2025; Raufflet, 2000; Tenza-Peral et al., 2023a). Their dynamics result from the interplay between internal components such as farmers, agricultural practices, natural resources and governance structures, and external drivers of change, such as climate variability, market pressures, policy shifts and sociocultural transformations (Hanspach et al., 2014; Tenza-Peral et al., 2019). These complex dynamics have been particularly evident in livestock farming systems in many regions of Europe, where external pressures have contributed to significant structural changes. Understanding how farming systems respond to these drivers is key to strengthen their resilience in the face of Global Change (Bilotto et al., 2024; Darnhofer, 2021).

Among livestock farming systems in Europe, sheep farming has experienced a marked and sustained decline over the past few decades. Between 2003 and 2023, the number of sheep in the European Union (EU) has decreased by 22% (Eurostat, 2024). The population of sheep in EU is mainly located in Mediterranean areas, where extensive sheep farming has traditionally supported rural livelihoods and has played a key role in exploiting lands with low agricultural potential, such as fallows and mountain pastures (Boyazoglu and Hatziminaoglou, 2002; Dubeuf et al., 2016). Thus, the disappearance of sheep farms implies the loss of cultural values, high quality meat and dairy products, and multiple ecosystem services, such as forest fire prevention and biodiversity conservation (Bernués et al., 2014; De Rancourt et al., 2006; Ribeiro et al., 2014). The decline of sheep farming systems in Europe has been related to different drivers, such as low farm income and low attractiveness of sheep farming to young farmers (Belanche et al., 2021). This evidences their limited resilience, which is the ability of farms to cope with social, economic, environmental and political challenges though robustness, adaptation and transformation capacities (Meuwissen et al., 2019). However, the extent to which different drivers have simultaneously determined the dynamics of these systems remain unexplored. This paper uses a system dynamics approach to investigate the decline of sheep farming systems in Mediterranean areas and to quantify the influence of different drivers on their dynamics.

System dynamics is a methodological approach designed to analyse complex systems based on the premise that a system's structure, including its components and the interactions between them, determines its behaviour over time (Sterman, 2000). It adopts a problem-oriented perspective, aiming to improve understanding of real-world challenges and to support decision-making (Costanza and Ruth, 1998; Tenza-Peral et al., 2020). System dynamics studies are generally based on two complementary approaches: qualitative modelling to build conceptual models that hypothesise the system structure based on peoples' understanding and experiential knowledge (Luna-Reyes and Andersen, 2003), and quantitative modelling to reproduce and explain the dynamics of the system based on computer simulation models (Sterman, 2000). The approach has been widely used in farming systems to investigate the relationships and the evolution of their components (e.g., farms or animals) and the root causes of diverse problems (Feola et al., 2012; Turner et al., 2016).

Studying the dynamics of farming systems requires to consider their social, economic and environmental dimensions (Darnhofer et al., 2012). Following this premise, several studies have developed simulation models to address different topics in livestock farming systems. For example, the sustainability and resilience of crop-beef systems in France or the United States (Herrera and Kopainsky, 2023; Walters et al., 2016), the effect of social-ecological drivers on the use and maintenance of common property pastures in Switzerland (Baur and Binder, 2015), and the long-term changes affected by regional and global drivers of change in Mexico (Tenza-Peral et al., 2019). These studies provide useful insights on the complex interrelations of livestock systems components and the drivers affecting them. However, they are not suited to the context of sheep farming in Mediterranean areas due to different key aspects such as feed management, climate and the influence of the Common Agricultural Policy (CAP).

The dynamics of livestock farming systems in Mediterranean areas have been explored through several approaches. Debolini et al. (2018) conducted a literature review and identified that abandonment due to socio-economic drivers was the main process affecting extensive livestock systems. Dubeuf et al. (2016) analysed official statistics and highlighted that the sheep numbers and the consumption of sheep meat greatly decreased in Southern Europe. Ribeiro et al. (2014) applied cluster analysis to describe farming dynamics encompassing CAP transformations and found that decoupling of payments from production could promote shifts from the traditional cereal-fallow-sheep system towards specialized livestock grazing systems. Similar results were obtained by Caballero and Fernández-Santos (2009) and Bernués et al. (2011), who used data records to assess the dynamics of sheep systems and found that flock sizes tended to increase while the number of flocks declined. Soriano et al. (2024) used qualitative system dynamics to develop a conceptual model of an extensive sheep farming system. Although these studies provided an overview of the drivers influencing sheep farming system dynamics, they were mostly based on qualitative analyses or statistical inference. As such, they did not capture the underlying structure of the systems or the feedback mechanisms through which drivers interact with system components over time, nor did they allow for a quantitative assessment of how these drivers influenced system dynamics.

This paper presents a simulation model designed to better understand the dynamics of sheep farming systems, considering their social, economic and environmental components, as well as the external drivers influencing their evolution. The model was built based on the case of the meat sheep farming system in Aragon (North-East of Spain), as a paradigmatic example of Euro-Mediterranean meat sheep systems that have sharply declined in the last decades. The period under study covered 2000 to 2022, and the modelling process considered multiple sources of information, including stakeholder knowledge, statistical databases and scientific papers. The model aimed at a more comprehensive view of the system's dynamics than previous studies focusing on isolated components and drivers were able to provide (Caballero and Fernández-Santos, 2009; Debolini et al., 2018; Dubeuf et al., 2016; Ribeiro et al., 2014). In addition, the model adds to previous research based on qualitative systems dynamic modelling (e.g., Soriano et al., 2024) by including quantitative data on key system components and enabling the assessment of the effects of external drivers on them over time. Our results raise important questions about the long-term resilience of extensive sheep farming systems and the strategies and policies required to sustain them under shifting global conditions.

The remainder of this paper is structured as follows. First, we describe the case study and the modelling approach. We then detail the model structure and the relationships among system components. This is followed by an analysis of the dynamics driving the decline of sheep farming and the influence of different external drivers. Finally, we discuss the main findings and their implications on livestock farming systems in Euro-Mediterranean areas.

2. Methods

2.1. Study system

We conducted our study for the meat sheep farming system in Aragon, a region located in the North-East part of Spain and covering 47,720 km^2. This system is representative of sheep farming systems dedicated to meat production in Mediterranean areas (De Rancourt et al., 2006). The study system has experienced a sharp decline in the last decades: the number of ewes has decreased by 46% between 1996 and 2023 (MAPA, 2024a). Some studies have shown that the system has low resilience and is struggling to cope with a variety of social, economic and environmental challenges (Belanche et al., 2021; Paas et al., 2021). Among the most important challenges are the lack of generational renewal and the dependence on CAP subsidies (Soriano et al., 2024). The lack of generational renewal has been related to marginality of rural areas where farms are usually located, to heavy workload associated with sheep extensive farming and to prices volatility, which makes profitability uncertain (Bertolozzi-Caredio et al., 2020). Dependence on CAP subsidies is also a major challenge because it makes farms vulnerable to changing agricultural policy goals, increasing bureaucracy and control requirements (Paas et al., 2021). However, this farming system has traditionally been very important in the region and despite the generalised decrease in lamb consumption, Aragon's sheep population and per capita consumption of lamb is still among the highest in Spain (MAPA, 2024b; MAPA, 2023).

Farmers keep 910–980 ewes per farm, although standard deviations equalling around 600 ewes indicate a wide variability (Pardos et al., 2022; Prat-Benhamou et al., 2025). Farms are usually mixed with crop production and, depending on the area, use feed resources from rainfed and irrigated crops (Pardos et al., 2022). Sheep use different grazing resources, such as fallows and rangelands, depending on the location and the season. On average, farms in the region account with 143 ha of UAA (Utilised Agricultural Area) and 1027 ha of mountain grazing resources (Pardos et al., 2022). Usually, ewes and lambs are supplemented with concentrates, maize and/or barley, alfalfa and straw (Barrantes et al., 2009), mainly at the end of pregnancy and during lamb rearing. The proportion of purchased feed in farms (mainly including concentrates) is around 40% (Prat-Benhamou et al., 2025). Most farms follow a reproductive program consisting of three lambings every two years, although five lambings every three years is also common and one lambing per year is also in place in some cases. This makes production stable along the year. As result, 1.4 lambs are sold per ewe in one year on average (Pardos et al., 2022). Part of the lambs are marketed under the Protected Geographical Indication "Ternasco de Aragón". The system is based on "Rasa Aragonesa" and other local breeds adapted to continental climatic conditions, characterised by large temperature fluctuations, intense sunlight, and scarce and unevenly distributed rainfall (Ferrer-Pérez et al., 2020). Farms account with 1.7 AWU (Annual Working Units) on average and family labour is predominant (1.4 AWU), although there has been an increase of wage labour over time (Pardos et al., 2022; Pardos et al., 2008).

2.2. Model scope and modelling approach

We built a dynamic simulation model to reproduce the historical dynamics of the meat sheep farming system in Aragon, and to better understand the endogenous and exogenous factors responsible for its decline. The model is designed to reproduce system-level behaviour at the regional scale, focusing on aggregate patterns emerging from the interaction of system components. Accordingly, the model relies on average values assumed to be representative of the system, and actors and farms are not differentiated by individual characteristics. Consistent with the defined system boundaries, the economic dimension of the model focuses on income related to the sheep farming activity, including market income and CAP support. Income from other agricultural or non-agricultural activities, as well as off-farm income, is not included due to limitations in data availability.

System dynamics is a methodological approach that aims to analyse and respond to real-world problems from a holistic point of view. Under this approach, the structure of complex systems (i.e., the components and their relationships) is responsible for the system's behaviour. Complexity arises from the existence of non-linearity, feedback loops, and delays in the flows of matter, energy and information between system components (Sterman, 2000; Tenza-Peral et al., 2020).

Building a dynamic simulation model is an iterative process that fosters a deeper understanding of the system under study, involving three main stages (Tenza-Peral et al., 2020): 1) conceptual model development, 2) quantitative model formulation and validation, and 3) simulation analysis. This study focuses on the last two stages of the modelling process. The conceptual model was developed using expert knowledge and was subsequently refined, expanded, and validated through a participatory workshop involving key stakeholders. A technical description of this participatory process can be found in Tenza-Peral et al. (2023b).

The conceptual model was then translated to a dynamic simulation model by defining mathematical equations suitable to define the relationships between system components, referred to as variables. System dynamics models comprise five types of variables. Stock variables represent accumulations or the quantity of a variable at a given point in time (e.g., number of farms). Flow variables determine the rates of change in stock variables over time (e.g., farms closure). Parameters (e.g., culling rate) and auxiliary variables support the definition of flows; parameters are fixed or constant values, while auxiliary variables are intermediary variables calculated within the model. Finally, external variables or forcing functions affect system dynamics but are not influenced by the system itself (e.g., precipitation index).

2.3. Model description and data collection

We used VENSIM DSS 10.3.1 to develop our model SHEEPSES (Sheep Social-Ecological System). The model simulates the dynamics of the meat sheep farming system in Aragon from 2000 to 2022 with an annual time step. Our focus was to simulate and analyse the number of farms, the number of animals, and the profitability of sheep farming. The model comprised 150 variables, including 3 stock variables, 47 parameters and 20 external variables. Only three parameters used to weight external variables were estimated using VENSIMS's automatic calibration tools, which identify the optimal values that enhance the model's fit to the available observed data. To facilitate the visualisation of the model, we divided it in four interconnected submodels: sheep production submodel, social submodel, economic submodel and feed management submodel. In the graphical representations of the submodels, the influence of exogenous variables on model variables is depicted with red arrows. The arrows indicate causal relationships between components, meaning that the component from which the arrow originates causes the change in the component to which the arrow points. A simplified version of the submodels can be seen in upcoming sections. A full model visualisation can be found in Supplementary Material 1.

The key performance indicators (KPIs), defined as variables that capture the most relevant aspects of the system, were the number of ewes and the number of farms (modelled as stock variables), and the net income per farmer (an auxiliary variable), used as a proxy for profitability. We used several data sources to build the reference mode (i.e., the real values observed over time) of the KPIs used for model calibration and validation, and to define the values of external variables and model parameters. These sources included national statistics, research papers and farm databases collecting technical and economic data (e.g., FADN database (MAPA, 2024c)). For the reference mode of the KPIs and external variables, when data sources contained data for several farms in several years we used mean values per year; and when data sources provided single values per year, these were used. For parameters, data corresponded to mean values in the hold data set considering multiple years when available. In this case, we analysed temporal trends to avoid using averaged values when a clear increasing or decreasing pattern was observed. All variables with a monetary value (euros) were deflated with the consumer price index (CPI) with base 2021 (INE, 2024). Thus, the values in the model correspond to the values in the original data sources after deflation. Details on data sources and elaboration can be seen in Supplementary Material 2 and 3. In the following sections, we describe the main variables and relationships included in each submodel. The variable names are depicted in italics throughout the text and a full description of variables and equations is available in Supplementary Material 3.

2.3.1. *Sheep production submodel*

The sheep production submodel focuses on the number of ewes and the number of lambs sold (Fig. 1). *Ewes* is a stock variable that represent the number of ewes, and it is defined by the input flows *Lambs weaned* and *Purchase of ewes*, and the output flows *Lambs sold*, *Ewes sold* and *Dead ewes*. *Lambs sold* increases with *Lambs weaned*, which depends on *Weaning rate*.

Purchase of ewes occurs for two reasons: to stock new farms (*Farms opening*) and to increase ewe numbers on existing farms. The latter is activated when the system identifies a gap between the current number of ewes and the *Labour-based sustainable number of ewes*, which defines the number of ewes that can be present in the system according to available labour. This difference is captured by the auxiliary variable *Balancing number of ewes*. When this value is positive and cannot be met through *Replacement* alone, additional ewes are purchased. Conversely, when the flock exceeds the labour-based threshold (i.e., *Balancing number of ewes* is negative), *Ewes sold* increases.

2.3.2. *Social submodel*

The social submodel focuses on two main aspects, the number of farms and the availability of labour in the system (Fig. 2). *Farms* is a stock variable, updated through the flows *Farms opening* and *Farms closing*. The rate of generational renewal drives both flows. Higher *Generational renewal rate* increases *Farms opening* and reduces *Farms closing*. This rate is influenced by two factors: the *Attractiveness of rural areas factor* (proxied by the proportion of population living in rural areas in Aragon) and the *Quality of life factor* (calculated as the ratio between income per hour for young farmers and income per hour in non-agricultural sectors, such as industry, construction, and services). When either factor increases, the number of farms tends to rise.

The *Quality of life factor* reflects both economic returns and workload. It increases when the *Income per hour for young farmers* is higher than in non-agricultural sectors. The *Income per hour for young farmers* is affected by the *Public support to young farmers*, which is treated as an additional income stream added to the *Net income per farmer* over a five-year period. The *Quality of life factor* decreases with *Total workload per farmer*, which depends on the *Ewes management workload per WU* and the *Paperwork burden per farmer,* which rises when the *Proportion of income from subsidies* increases, due to greater administrative requirements.

In addition to generational renewal, farms may exit the system when *Net income per farmer* falls below a minimum threshold, triggering *Farms closure due to economic losses.*

The number of farms determine *Family labour* in the system, based on the *Family labour needed per farm*. This, in turn, depends on the *Labour needed per farm,* which is calculated from the *Desirable number of ewes per farm.* The latter is derived from the land-based carrying capacity (i.e., *Land-based sustainable number of ewes per farm*) and the minimum economic threshold (i.e., *Minimum number of ewes per farm),* as defined in the economic and feed management submodels.

When *Labour needed per farm* exceeds the *Average family labour per farm, Wage labour* is required. However, the availability of wage labour is constrained by the *Opportunity cost factor,* which compares the average wage of sheepherders with that of similar unskilled workers. If this factor is below 1, not all labour needs can be met. In such cases, only the *Potential wage labour* is hired (i.e., a portion of the wage labour needed).

Family labour and *Wage labour* determine the *Labour-based sustainable number of ewes*, a key output of this submodel that feeds into the sheep production submodel by defining the system's labour-based carrying capacity.

2.3.3. *Economic submodel*

The economic submodel focuses on *Net income per farmer*, used as an indicator of system profitability (Fig. 3). This variable depends on *Net income per farm* and the *Subsidies per farm*. Higher values for either component result in a higher *Net income per farmer*, which in turn

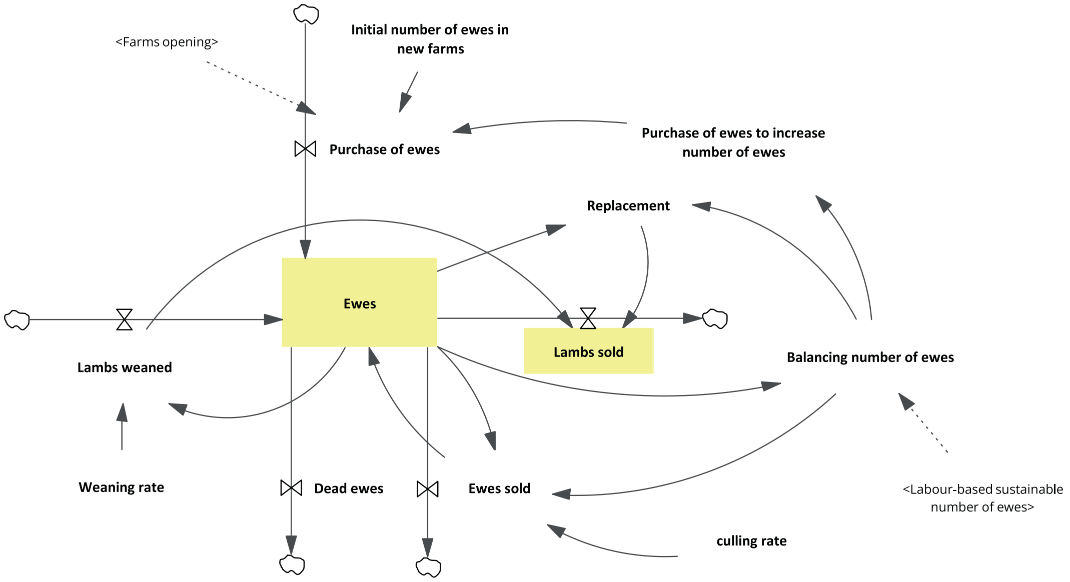

Fig. 1. Simplified version of the sheep production submodel. Variables within "<>" and followed by dashed lines are described in other submodel sections.

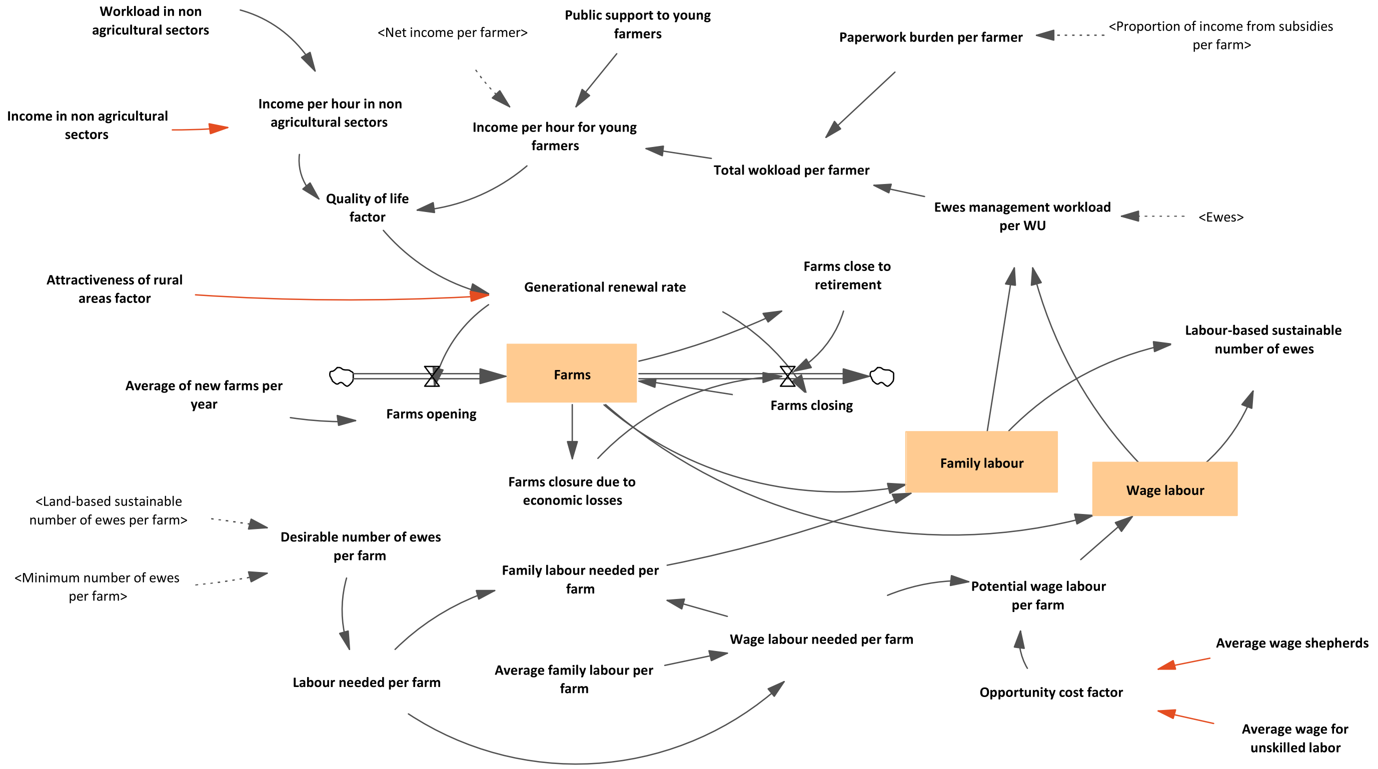

Fig. 2. Simplified version of the social submodel. Variables within "<>" and followed by dashed lines are described in other submodel sections. Variables followed by a red arrow are exogenous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

positively influences the number of farms in the system (see Section 2.3.2. Social submodel).

Net income per farm is calculated as the difference between *Income from sales* and the *Production cost*. *Income from sales* is determined by the number of lambs sold and their price, across two marketing channels: conventional lamb and PGI-certified "Ternasco de Aragón". Lamb prices in both channels are external variables. While PGI lambs generally reach higher prices, they are also more volatile. Conventional lamb prices follow a decreasing trend. This combination leads to a lightly descendent trend in income per farm over the simulation period.

Production cost includes three main components: *Wage labour cost*, *Feed cost* for ewes and *Feed cost for lambs*. Labour costs depend on the number of hired workers (i.e., *Wage labour*) and their average wage (i.e., *Average wage shepherds*). Feed costs are calculated based on the quantities of straw, alfalfa and concentrate required, as well as their market prices. In addition, an aggregated component (*Other costs per farm*) is included to represent other production costs, such as family labour costs, animal health costs and financial costs, among others (see Supplementary Material 3 for details). All these input prices (including *Average wage shepherds*) are treated as external variables and increase over time, contributing to rising production costs.

Subsidies per farm are modelled according to two main CAP regimes: *Coupled payments per farm 2000–2005* and *Decoupled payments per farm 2006–2022*. This distinction reflects the shift in the Common Agricultural Policy (CAP) from animal-based to land-based support. Coupled payments are determined by the subsidies given per animal type (i.e., ewes, replacement ewes and ewes located in disfavoured areas), while decoupled payments are determined by the subsidies given per hectare of UAA, livestock subsidies and other subsidies per farm. All unitary subsidy values (per ewe or per hectare) are external variables. The total amount of subsidies received per farm thus varies depending on both the payment regime and the farm characteristics.

Additionally, the submodel calculates the *Minimum number of ewes per farm*, considering the *Net income with subsidies per ewe*, the *Minimum expected net income* per family worker and the *Average family labour per farm*. This indicator feeds into the social submodel to define the *Desirable number of ewes per farm*. Lastly, the model calculates the *Proportion of income from subsidies per farm*, which is used in the social submodel to estimate the *Paperwork burden per farmer*.

2.3.4. *Feed management*

The feed management submodel focuses on how farms use the land to produce feed for ewes (Fig. 4). Two main land resources are considered: agricultural land and mountain grazing areas.

Agricultural land is represented by the stock variable *UAA for ewes*, with *Hectares in* and *Hectares out* as input and output flows. The inflow reflects the increase in UAA per farm multiplied by the number of farms, while the outflow represents the loss of UAA due to farm closures. Within this area, we differentiated the *UAA of rainfed crops used* and the *UAA of irrigated crops used* based on the proportion of these land types managed by farmers in the region. *Mountain grazing resources used* are calculated based on the on the average use per farm and the number of farms.

From these land types and their respective nutritional value (expressed in feed units, FU, per hectare), the model estimates *Total feed resources produced*. These values are then adjusted for annual climatic variation using the *Precipitation index*. This index modifies feed productivity according to wet or dry conditions, through the *Precipitation effect on vegetation productivity*, resulting in the final *Effective feed resources produced*.

The proportion of feed sourced on-farms depends on the *Effective feed resources produced* and determines the *Effective proportion of on-farms produced feed*. When precipitation is above average, this proportion increases; when below average, it decreases. The model uses this relationship to adjust the *Average proportion of on-farms produced feed* and to estimate the amount of feed units actually produced on-farms (*FU produced on-farms*).

By comparing the total feed required by ewes (*FU required per ewe*

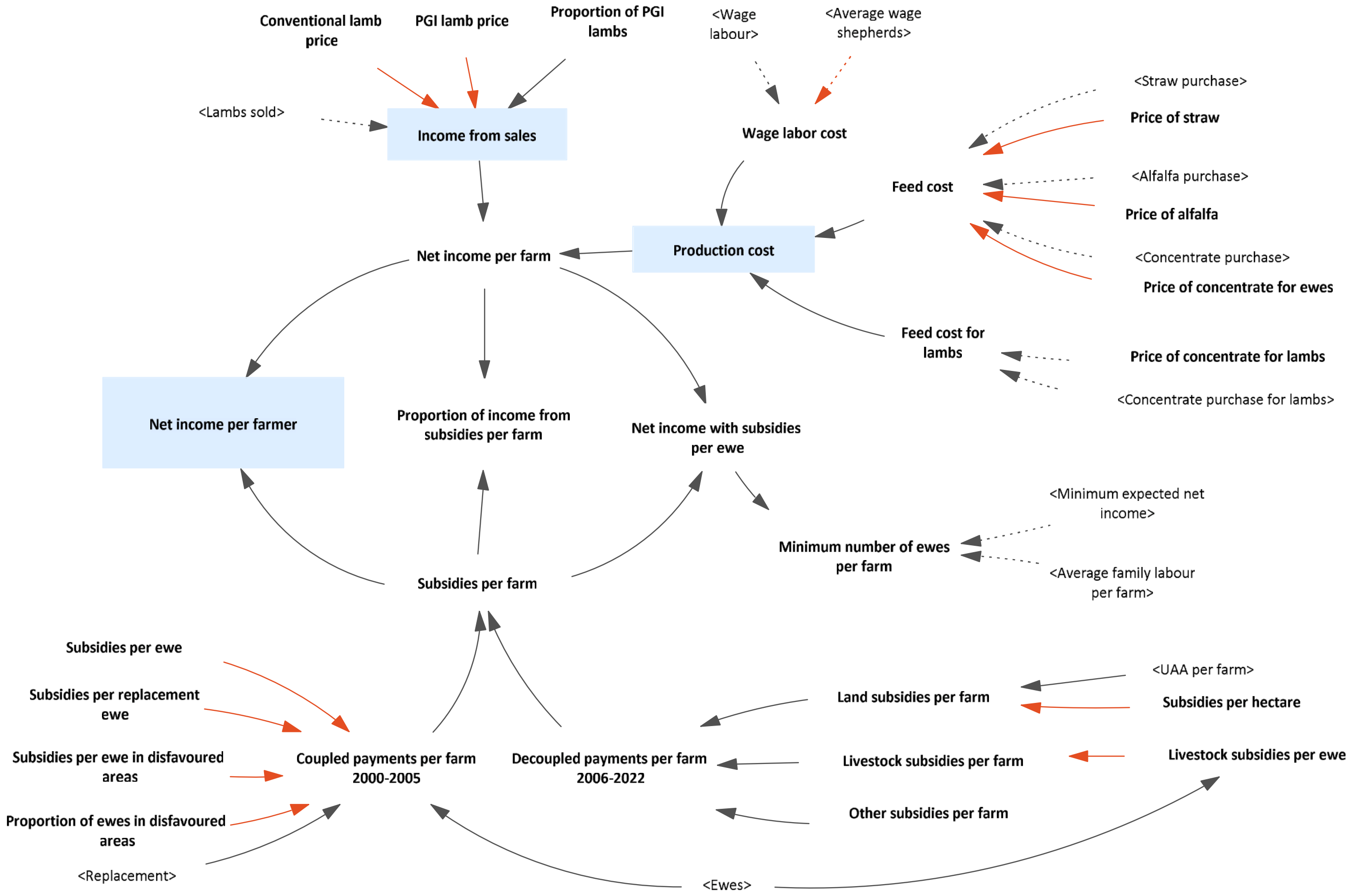

Fig. 3. Simplified version of the economic submodel. Variables within "<>" and followed by dashed lines are described in other submodel sections. Variables followed by a red arrow are exogenous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

multiplied by the number of ewes) with the available on-farm feed, the model calculates the *Total FU deficit*. This deficit is covered through the purchase of straw, alfalfa and concentrate, based on their nutritional value and the share of each in the ewe's diet. In addition, *Concentrate purchase for lambs* is included as a function of the average purchase per lamb and the number of lambs sold.

Finally, the model calculates the *Land based sustainable number of ewes per farm* based on *Effective feed resources produced*, *Farms*, and *FU required per ewe*. This variable represents the maximum number of ewes that can be sustained in a farm considering the amount of feed produced on the available land. It is used in the social submodel to define the *Desirable number of ewes per farm*. Lower feed availability reduces the desirable number and, ultimately, the total number of ewes in the system.

2.4. Model testing

To assess the level of confidence in the model, we evaluated its robustness, reliability, and validity through structural tests, sensitivity analyses, and behavioural tests (Barlas, 1996; Barlas, 1989; Solecki and Oliveri, 2004). These tests enabled us to detect errors, identify model limitations, and improve its structure.

Confidence in such models is primarily grounded in their ability to reproduce the expected logical behaviour of the real system, even under conditions beyond those used for calibration. To verify this, we examined the consistency of model units, extended the simulation time horizon to detect potential long-term anomalies, and conducted a series of extreme condition tests to assess internal consistency (e.g., if the number of farms or labour decreases to zero, the number of ewes should also decline to zero). The model successfully passed the key structural tests without exhibiting any unexpected behaviour.

Sensitivity analyses test how the behaviour of the model is affected by changes in parameter values (Banos-González et al., 2018; Bala et al., 2017). Model behaviour must be driven by the model structure (e.g., relations and feedbacks) and changes in model parameters should not modify the behavioural patterns. This also constitutes an uncertainty analysis (Banos-González et al., 2018), as uncertainty arises both from a lack of knowledge regarding the precise values of certain parameters (e.g., those calibrated using automatic calibration tools) and from the intrinsic variability present in other parameters (e.g., *Precipitation effect on vegetation productivity*). Each sensitivity analysis consisted of 200 model runs in which the parameter values were changed. We conducted two local sensitivity analyses (i.e., varying one parameter at a time). In the first analysis, all model parameters were varied by ±50% from their baseline values to identify those to which the model was most sensitive. For parameters showing moderate to high sensitivity, a second local sensitivity analysis was performed using a narrower and more realistic variation range of ±25% (Banos-González et al., 2018; Taylor et al., 2010). Also, we made a global sensitivity analysis (i.e., varying several parameters at a time) by Monte Carlo simulations (Banos-González et al., 2018; Taylor et al., 2010). The results indicated that the model is robust, as its behavioural pattern remained consistent despite changes in parameter values. More details on the sensitivity analyses can be found in Supplementary Material 4.

Behavioural tests are used to measure how accurately the model can reproduce the dynamics of the real system (Bala et al., 2017; Oliva, 2003; Sterman, 1984). Although it is important for the model to behave similarly to the real system, achieving satisfactory results in these tests is

Fig. 4. Simplified version of the feed management submodel. Variables within "<>" and followed by dashed lines are described in other submodel sections. Variables followed by a red arrow are exogenous. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not enough to build confidence in the model. The model interpretation should focus on patterns rather than predictions (Bala et al., 2017; Sterman, 2000). We made the behavioural reproduction tests using descriptive statistics included in the Theil Module Tool developed for Vensim (Oliva, 1995; Sterman, 1984) and additionally, we calculated the normalised mean squared error (Andarzian et al., 2011; Loague and Green, 1991). The results showed a good agreement between simulated and observed data on the KPIs, especially for ewes. A more detailed description of the results can be found in the Supplementary Material 5.

2.5. Simulation analysis

Following model testing, we explored the base simulation (i.e., baserun, presented in Section 3.1) using a "feedback story" approach to understand how the KPIs changed over time and what feedback mechanisms caused their behaviour. In addition, we made 13 experimental simulations to assess the impact of the main external drivers of change (i.e., external variables) on the historical dynamics of the system.

In each experimental simulation, we modified one external driver either by removing its effect entirely or by holding its value constant throughout the simulation period. This allowed us to explore counterfactual scenarios addressing the question "what would have had happened if…?"

To quantify the influence of each external driver, we calculated a variation coefficient that compared the values of the KPIs in the *baserun* with those obtained in the experimental simulations at the final simulation time (see Supplementary Material 6 for the equation used). In addition, we calculated the variation coefficients for the average value and the standard deviation of each KPI over the entire simulation period. The variation coefficients range from −100% to +100%, where values near zero indicate minimal impact and values approaching ±100 indicate maximum impact on the KPI.

We classified the experimental simulations into three groups: social, economic, and feed management drivers of change. The social drivers group included four simulations: (1) quality of life is equal compared to non-agricultural sectors (*Equal quality of life*), (2) rural attractiveness remains constant over time (*Initial attractiveness of rural areas*), (3) no subsidies are given to young farmers (*No subsidies for young*), and (4) no lack of labour (*All labour needed available*).

The economic drivers group included six simulations: (1) no subsidies are given to farms (*No subsidies*), (2) lamb prices fixed at their initial value (*Initial lamb prices*), (3) lamb prices fixed at their average value (*Average lamb prices*), (4) there is no PGI "Ternasco de Aragón" (*No quality differentiation*), (5) input prices (considering feed and wage of shepherds) fixed at their initial value (*Initial input prices*), and (6) input prices fixed at their average value (*Average inputs prices*).

The feed management drivers group included three simulations: (1) precipitation is normal over time (i.e., precipitation index equals 0, *Normal precipitation*), (2) there is no increase in UAA used per farm (*No increase in UAA*) and (3) farms do not use mountain pastures (*No mountain pastures*).

A detailed description of the experimental simulations, including the variables modified, is provided in Supplementary Material 6.

3. Results

3.1. Baserun simulation results

Fig. 5 shows the evolution of the KPIs in the simulation period. The number of farms decreased constantly over the simulation period, as farms opening was low compared to farm closure. This trend is related to a low generational renewal: only about 50% of the existing farms had generational renewal across the simulated period. The lack of generational renewal was driven by several factors. First, because the *Attractiveness of rural areas* (i.e., proportion of population living in rural areas) was low (around 0.27). Second, the *Quality of life factor* (i.e., income per hour compared to non-agricultural sectors) decreased, showing that farmers' life quality was lower in sheep farming compared to non-agricultural sectors until 2012. From 2013 it was also lower but tended to increase because of the *Public support to young farmers*. Thus, from 2013 to the end of the simulation period, the *Quality of life factor* changed the tendency to stabilise and later increase. Still, it is interesting to highlight that farmers worked more hours compared to non-agricultural sectors but also farmers earned more money. This is why the net income per hour was not very different quantitatively, but it was qualitatively different because farmers workload was higher, resulting in a lower perceived quality of life. Also, the time farmers worked for sheep was constant, but the time dedicated to paperwork increased.

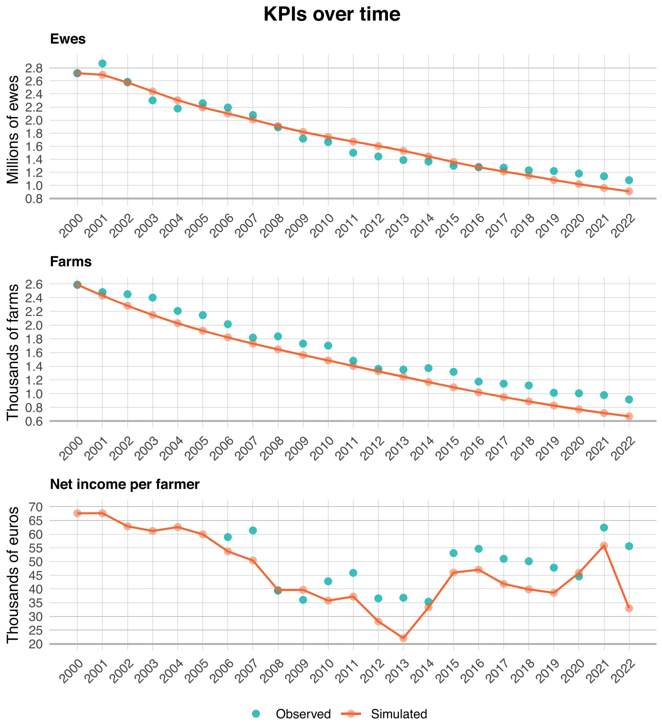

Fig. 5. Evolution of the Key Performance indicators (KPIs) over time (years 2000 to 2022). Observed data corresponds to real values over time according to data sources described in Supplementary Material 2, and simulated data corresponds to model outputs.

As the number of farms declined, both *Family labour* and *Wage labour* in the system also decreased. This led to a reduction in the *Labour-based sustainable number of ewes,* and consequently, in the total number of *Ewes* throughout the period.

Despite this overall decline, the *Desirable number of ewes per farm* increased over the simulation. This was driven by an increase in the *Land-based sustainable number of ewes per farm*, which resulted from the expansion of UAA used per farm. Consequently, the number of ewes per farm rose, leading to greater *Labour needed per farm* and, subsequently, increased *Wage labour needed*. The *Wage labour per farm* increased; however, the *Potential wage labour per farm* remained consistently below the actual demand, as the *Opportunity cost factor*, which reflects the relative attractiveness of shepherd wages compared to other unskilled jobs, remained below 1.

Net income per farmer varied along the simulation period. There were several spikes explained by the annual variations in incomes and costs, but overall, the tendency was descendent until 2013 and then it started to rise. The decreasing trend in *Net income per farm* occurred because the increase of *Production cost per farm* could not be compensated with the increase in the *Income from sales per farm*. This was mainly because the market prices of lambs decreased while prices of inputs increased.

Regarding *Subsidies per farm*, *Coupled payments per farm 2000–2005* showed a slightly decreasing trend. *Decoupled payments per farm 2006–2022* were initially stable (2006–2012), followed by a gradual increase from 2013 onwards. The decoupled payments were structured to pay per hectare of *UAA per farm*, i.e., more money was dedicated to *Land subsidies per farm* and less to *Livestock subsidies per farm*. We observed that *Land subsidies per farm* tended to increase due to an increase in the *UAA used per farm*, although the amount of money paid per *UAA used per farm* decreased. Thus, although the CAP reforms changed the structure of payments, we observed that the amount of money received from subsidies remained similar across years, showing an ascendent trend from 2012 onwards. Also, we observed that farms used more UAA, which helped to increase the amount of money received through decoupled payments. The *Proportion of income from subsidies per farm* was about 0.47 in 2000 and about 0.80 in 2022, showing an increasing trend during the entire simulation period.

Notably, in some years, *Net income per farm* fell below zero. This highlights the growing importance of subsidies in sustaining farm income. The increasing dependency on subsidies also contributed to a perceived rise in the *Paperwork burden* among farmers during the simulation period.

3.2. Effects of external drivers

Table 1 shows the main results of the experimental simulations. Overall, the economic drivers had the highest impact on the KPIs. The impact of economic and feed management drivers was mainly negative; the impact of social drivers was mainly positive. A negative impact indicates that, under the conditions simulated, the KPIs values would have decreased; conversely, a positive impact suggests that the KPIs values would have increased. For *Farms* and *Ewes*, which are stock variables representing accumulations over time, the variation at the final time is the most informative. In contrast, for *Net income per farmer*, an auxiliary variable acting as a performance indicator, the variation in the mean value offers the most relevant insight.

Most of the simulations including social drivers (i.e., *Equal quality of life*, *Initial attractiveness of rural areas* and *All labour needed available*) showed an increase on *Farms*, *Ewes* and *Net income per farmer*. Especially, the simulation *All labour needed available* had the strongest effect among the simulations including social drivers, with *Ewes* increasing by +52% at the end time. *Equal quality of life* led to increases of +9% in both *Ewes*

Table 1

Results of the experimental simulations including the coefficients of variation (%) of *Farms*, *Ewes* and *Net income per farmer* calculated at the final simulation time, as well as for the mean and the standard deviation (SD) over the full simulation period.

Simulation name	Farms			Ewes			Net income per farmer	
	End time	Mean	SD	End time	Mean	SD	Mean	SD
Equal quality of life	9.1	0.1	−4.9	9.1	0.2	−6.1	−0.1	0.1
Initial attractiveness of rural areas	1.0	0.1	−0.3	1.0	0.1	−0.4	0.0	0.0
No subsidies for young	−2.2	−0.2	0.6	−2.2	−0.2	0.8	0.0	0.0
All labour needed available	8.1	3.8	−3.1	52.9	30.0	1.1	8.5	27.1
No subsidies	−100.0	−38.7	63.4	−100.0	−40.8	82.6	−71.0	2.5
Initial lamb prices	19.2	4.1	−7.9	19.1	4.4	−10.3	27.3	−33.5
Average lamb prices	−4.5	−4.3	0.1	−4.5	−4.4	0.6	1.0	−31.1
No quality differentiation	−3.5	−0.6	1.7	−3.5	−0.7	2.1	−7.4	4.8
Initial input prices	13.1	2.3	−5.2	12.3	2.7	−5.7	22.4	−31.5
Average inputs prices	−16.1	−8.6	4.5	−16.9	−8.7	7.4	−14.8	−28.3
Normal precipitation	0.7	0.2	−0.6	−0.7	0.9	−2.3	0.4	−3.2
No increase in UAA	−15.2	−2.4	6.6	−27.4	−6.9	16.6	−21.9	52.2
No mountain pastures	−20.8	−14.0	6.6	−64.8	−69.3	−35.2	1.2	208.5

and *Farms*, while *Initial attractiveness of rural areas* resulted in a modest +1% rise. In contrast, *No subsidies per young* showed slight decreases of approximately −2% in *Farms* and *Ewes*.

In the simulations including economic drivers, we observed that *Farms*, *Ewes* and *Net income per farmer* decreased in most of the simulations. In particular, *No subsidies* caused a complete system collapse, with *Farms* and *Ewes* falling to zero. In *Average inputs prices, Farms* and *Ewes* decreased by −14% to −17%, and *Net income per farmer* dropped by −15% on average. The other simulations in this group showed smaller negative effects. Conversely, *Initial lamb prices* and *Initial input* prices led to increases in *Ewes* and *Farms* ranging from +13% to +28%, and *Net income per farmer* increased by +22% to +28% on average.

The simulations including feed management drivers showed that in *No increase in UAA* and *No mountain pastures*, *Farms* decreased by −15% to −20%. In addition, *No increase in UAA* showed an important decrease in the *Net income per farmer* (−22% on average) and *No mountain pastures* showed a remarkable −65% decrease of *Ewes*. In contrast, *Normal precipitation* had minimal impact, with variation coefficients close to zero.

4. Discussion

This paper presented a model that simulates the dynamics of the meat sheep farming system in Aragon from 2000 to 2022 considering its social, economic and environmental dimensions. The model was used to explore the dynamics of the system and to quantify the effect of external drivers on them. Thus, the model helped to understand empirically the interactions of the meat sheep farming system from a social-ecological systems perspective. The results highlighted that the social and economic dimensions where key to understand the dynamic of the system. More specifically, we found that the lack of generational renewal and the lack of labour caused the system decline (i.e., the decrease in the number of farms and ewes). Regarding the effect of external drivers, we ran several experimental simulations to analyse quantitatively what would have happened if the drivers had been different. In this sense, we found that CAP subsidies were essential to guarantee the system viability, as without these payments, the system would have collapsed. The results may help to disentangle the dynamics of other Mediterranean sheep farming systems, which are built through similar social, economic and environmental components and face similar challenges.

4.1. Dynamics of the system: What explained the decline

The lack of generational renewal led the system decline. This was mainly driven by the low attractiveness of rural areas and the low farmers' quality of life (i.e., income per hour compared to non-agricultural sectors). In the sheep farming system in Aragon, the lack of generational renewal has been linked in the literature to low profitability (often understood in aggregate income terms), high workloads and the poor attractiveness of rural areas where farms are located (Bertolozzi-Caredio et al., 2020; Paas et al., 2021; Soriano et al., 2024). However, our results suggest a different interpretation. We found that low profitability did not determine low generational renewal, as the income of farmers was higher than in non-agricultural sectors, even when excluding payments for young farmers. Instead, the factor determining low generational renewal was the higher workload (i.e., hours worked) compared to non-agricultural sectors.

The balance between farm income before subsidies and farm costs revealed that farms struggled to cover production costs through lamb sales. The income from lambs decreased, and input costs (mainly feed costs) increased over time. In turn, balance between income and costs was not enough to guarantee a minimum income for farmers, especially at the end of the simulation period. Thus, the profitability of farms depends on CAP payments. Several studies have pointed to this reliance on subsidies, with both positive and negative implications for the system. On one hand, Pardos et al. (2022) found that subsidies are perceived as positive by farmers, who would like to receive more payments accompanied by an increase in the lamb prices. On the other hand, Paas et al. (2021) consider that the increasing dependence on subsidies derives in increasing bureaucracy, which hampers farmers quality of life by increasing workload and control requirements.

The declining trend in the number of farms and sheep (i.e., abandonment) was accompanied by an increase in the agricultural land used, flock size and wage labour per farm, as also reported in previous studies (Bernués et al., 2011; Pardos et al., 2016). The increase in agricultural land is pursued by farmers because it can be used for crop production and animal feeding, but also because CAP payments are linked to the number of hectares. Thus, farms became fewer in number but larger and increased the land used. The increase in land used has been identified as a successful strategy to improve the economic performance of sheep farms in the region (Olaizola et al., 2015). The increase of available land encouraged farmers to increase their flock size by hiring labour, but this was limited by the labour willing to work in farms as suggested in previous research (Paas et al., 2021; Pardos et al., 2016). While the model captures this increase in agricultural land per farm as part of a broader process of structural change, it does not allow disentangling whether land expansion is primarily driven by efficiency-related considerations or by incentives linked to CAP payments.

4.2. Effects of external drivers: What would have happened

Economic drivers' influence on the system was the most important. Notability, the absence of subsidies would have led to a collapse of the system from 2013. This supports that the system has reached a critical threshold and without subsidies, sheep farming would not be economically sustainable (Paas et al., 2021). Our results also showed that the changes in the market prices of lambs and specifically, declining lamb prices and rising input costs reduced farms profitability, which reinforced the lack of generational renewal as described in previous studies (Soriano et al., 2024). The existence of the PGI marketing channel supported the profitability of farms. Thus, our results support the idea that input costs are an important risk factor for the decline of the system, and while the PGI supports farm income, it would not be sufficient to reverse the declining balance between income and costs (Bertolozzi-Caredio et al., 2021b).

Regarding social drivers, the quality of life, the attractiveness of rural areas and the opportunity cost were key to understand the decline of the sector. The lack of wage labour clearly influenced the number of ewes. In the study system, the lack of (skilled) labour has been identified as an important problem linked to the opportunity cost compared to other economic activities (Bernués et al., 2005; Paas et al., 2021; Soriano et al., 2024). The lower quality of life (i.e., income per hour compared to non-agricultural sectors) and the decrease in attractiveness of rural areas (i.e., population in rural areas) reinforced the decline of the system by decreasing generational renewal. In this sense, our results support that quality of life and attractiveness of rural areas are key to understand the dynamics of the system (Bertolozzi-Caredio et al., 2020; Soriano et al., 2024). In contrast, public support for young farmers slowed the decline of the system. However, the effect of these payments was limited. This aligns with Coopmans et al. . (2021) who indicated that the payments to young farmers marginally improved farm income and survivability in the early stages of farming but did not to affect the initial decision of farm entry. Similarly, Bertolozzi-Caredio et al. (2020) found that payments are only positive once a young farmer already inherited a farm.

Finally, regarding environmental drivers, the increasing use of agricultural land and the access to mountain pastures buffered system decline. The increase in agricultural land used helped to increase profitability, especially in the years of CAP decoupled payments (i.e., payments given per hectare instead of per animal). Our results contrast previous studies which hypothesised that decoupled CAP payments would reduce farm income (Manrique et al., 2006) and that these payments have accelerated the decline in the number of sheep and farms in the system (Pardos et al., 2022). However, decoupled payments may relate to the increase in agricultural land per farm that could promote changes in management patterns. In southern Portugal, Ribeiro et al. (2014) found a relationship between decoupled payments and agricultural transition from traditional cereal-sheep systems to specialized livestock systems. We suggest that the increase in agricultural area used by farms may drive a re-orientation towards crop production instead of mixed crop-livestock systems, especially for farm successors seeking a better quality of life (Bertolozzi-Caredio et al., 2021a). However, further research would be needed to investigate these processes.

Mountain pastures were also key to sustain the number of ewes in the system. These constitute a very important feed resource for sheep in the study area (Barrantes et al., 2009) and their use is key for the provision of ecosystem services (Bernués et al., 2014). Although mountain pastures play a crucial role in maintaining ewe populations, farmers are struggling to declare the use of these pastures to receive CAP payments (Pardos et al., 2022). This is related to the diversity of Mediterranean pastures used (Barrantes et al., 2009), many of which are poorly eligible for CAP payments (e.g., shrub and forest pastures). This reality contrasts with the aim of the CAP to support extensive farming systems.

Precipitation was not very important for the system dynamics due to the limited reliance of farms on on-farm produced feed. Although greater reliance on on-farm feed can enhance farm autonomy and reduce exposure to input price volatility (Ripoll-Bosch et al., 2014), it may also increase vulnerability to climatic events such as droughts (Janssen et al., 2007). Further research would be needed to test increasing feed autonomy would improve the dynamics of the system.

4.3. Policy implications

The system studied showed to be poorly resilient, especially regarding social, political and economic challenges. We found that quality of life (i.e., income per hour) in sheep farming is worse than in non-agricultural sectors because of workload. This suggests that policies should not focus solely on increasing the income of (young) farmers, as this has proven insufficient to address the issue of generational renewal. People's expectations on what is considered a valuable and enjoyable lifestyle are important to address the attractiveness of the farming profession (Coopmans et al., 2021). As young people's expectations are increasingly lifestyle oriented, potential solutions could focus on reducing farmers' workloads. For example, policies could promote support networks to assist with decision-making and administrative tasks or create services that provide skilled workers to temporarily replace farmers during holidays. These measures would also help address the shortage of wage labour, which is another key factor driving system decline.

Although CAP payments have prevented the collapse of the system, they have not succeeded in reversing the declining trend in the number of sheep and farms. The greater dependence on CAP payments makes farms vulnerable to changing conditions. While CAP support has contributed to system robustness, its effect on the adaptive and transformative capacity of farms remains limited (Slijper et al., 2022). Still, reverting the declining trend and improving the resilience of the system may require adaptation and transformation strategies (Paas et al., 2021). These may help to decrease their dependence on subsidies. For example, a system transformation towards short-channel commercialisation of meat may contribute to an increase in income from lambs (Soriano et al., 2024). This would benefit from public policies supporting the existence of small slaughterhouses in rural areas.

Mountain pastures were key to sustain the number of sheep over years, and the use of pastures provides ecosystem services to society. However, these contributions are not adequately recognized in the distribution of CAP payments. Farmers perceive that shifting from decoupled payments to payments for ecosystem services would be both fairer and more effective in strengthening system resilience (Pardos et al., 2022). Currently, the access and use of these mountain pastures is being limited by several drivers, such as the appearance of predators or the competition with wind turbines and solar panels in the region. We argue that although these drivers were not important in the past decades, they should be considered as potential constraints towards the future.

4.4. Strengths and limitations

System dynamics helped to improve the understanding on the evolution of the sheep farming system in Aragon. The simulation model was useful to contrast previous research based on qualitative data or predictive models. This provided insights into the factors contributing to the decline of the system considering the complex interrelationships among them that were lacking in previous research (Soriano et al., 2024). In this sense, the model can serve as a tool to support policy design aiming at slowing the decline of the system and improving its long-term resilience.

System dynamics models are built simplifying systems nature. In the study system farms vary in terms of size, structure, and land use (Pardos et al., 2008). Thus, the average values used for parameters and external data series might not reflect the performance of all farms. The model could be improved considering additional factors or processes. For example, generational renewal is influenced by successor willingness and farm-family dynamics (Coopmans et al., 2021). Also, the fact that lack of available land and the high investment costs may hamper the generational renewal, especially for new entrants to farming (Zagata and Sutherland, 2015). These factors could not be incorporated into the model due to lack of consistent quantitative data. The attractiveness of rural areas was calculated considering the proportion of people living in rural areas in Aragon. More specific data considering the density of rural areas, distances to basic services or the connectivity of networks (physical or social) might improve model results (Ayuda et al., 2023;

Debolini et al., 2018). In this line, we acknowledge that population in rural areas lightly decreased in the studied period, so the experimental simulation keeping attractiveness of rural areas as in 2000 showed a limited effect in the model. There was a major shift in rural population in previous decades that might have impacted the system before 2000 (Ayuda et al., 2023). In addition, the increase in the number of hectares per farm and the number of new farms were not calculated by the model, as modelling these processes was beyond the scope of this study. To address this limitation, we incorporated data from official databases.

5. Conclusion

The main conclusion of this study is that together with economic drivers, social drivers drove the decline in the number of farms and sheep. This was caused by a lack of generational renewal, which was a consequence of poor quality of life, largely driven by high workloads rather than low aggregate income, and low attractiveness of rural areas.

The system would have collapsed without the subsidies of the Common Agricultural Policy. However, policies based on economic premiums have proven insufficient to reverse the declining trend in sheep and farm numbers. Policies focused on improving farmers quality of life and the attractiveness of rural areas, and on decreasing the dependence on subsidies would increase the system resilience in the long term.

The model SHEEPSES was helpful to understand past dynamics and could be used to support policy design aiming at slowing the decline of the sheep farming.

CRediT authorship contribution statement

Alicia Prat-Benhamou: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Birgit Kopainsky:** Writing – review & editing, Supervision, Methodology. **Alberto Bernués:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Daniel Martín-Collado:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Alicia Tenza-Peral:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104811.

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