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Research

What shapes silvopastoralism in Mediterranean mid-mountain areas? Understanding factors, drivers, and dynamics using fuzzy cognitive mapping

Antonio Lecegui [1], *Ana M. Olaizola* [2,3], *Kasper Kok* [4] and *Elsa Varela* [5,6,7]

ABSTRACT. Silvopastoral systems, integrating woody vegetation and livestock farming, are increasingly recognized as a sustainable land-use supporting biodiversity and ecosystem services provision in the Mediterranean. However, this traditional practice has declined in recent decades, mainly because of land abandonment and intensification processes. We investigated the relationships between the factors involved in the dynamics of silvopastoralism in two contrasting Spanish case studies in Mediterranean mid-mountain areas: Sierra de Guara Natural Park and Lluçanès region. Combining semi-structured interviews with researchers and participatory workshops with key stakeholders, we built a Fuzzy Cognitive Map (FCM) representing the shared perception of forest grazing in each region and implemented methodological improvements in FCM post-processing and analysis leading to an improved understanding of FCM outcomes. Results revealed that the dynamics of forest grazing are highly influenced by the socioeconomic attractiveness of the farming sector because it was a central factor in both case studies, whereas the importance of other factors such as farm abandonment in Guara and access to land in Lluçanès were site-specific. Climate change and the Common Agricultural Policy (CAP) were identified as the main external drivers undermining forest grazing in both sites while the incidence of other economic activities (i.e., tourism or other livestock production systems) relied on the context of each region. In contrast, technological innovations, including GPS collars and virtual fencing, along with the existence of infrastructures such as water points and active forest management, were identified to promote beneficial feedback loops for forest grazing. Although the current policy framework is failing in fostering silvopastoralism, a policy shift from direct payments to result-based schemes for biomass reduction and wildfire prevention tailored to each region's environmental constraints and potentials would lead to better outcomes for society as a whole.

Key Words: *agroforestry; Common Agricultural Policy; feedback loops; participation; social-ecological systems; wildfire prevention*

INTRODUCTION

Silvopastoral systems, combining woody perennials with forage and livestock, have been an important traditional land use in Europe for centuries, with a higher occurrence in the Mediterranean countries (Plieninger et al. 2015). These semi-natural systems can be considered dynamic social-ecological systems that involve interactions and feedback between their social and ecological components (Hartel et al. 2018, Plieninger and Huntsinger 2018), supporting biodiversity conservation and the provision of multiple ecosystem services (Hölting et al. 2019). Silvopastoral systems provide a range of marketable products such as meat and wood while contributing to hydrological and carbon cycle regulation, soil fertility, wildfire risk reduction, and the provision of unique spaces for recreation, cultural, and aesthetic experiences (Torralba et al. 2016, Moreno et al. 2018, Lecegui et al. 2022a).

Although silvopastoralism is still a widespread practice in the Mediterranean, it has decreased in recent decades mainly because of agricultural intensification and land abandonment processes driven by multiple factors (Lasanta et al. 2015, Rodríguez-Rigueiro et al. 2021, Quintas-Soriano et al. 2022). These factors include the sociocultural transformations that have led to the depopulation of Mediterranean rural areas (MacDonald et al. 2000), the economic pressures from the increasingly competitive global markets and the technological advances that have also contributed to farm intensification, especially in more productive areas, but also in less productive ones such as those where silvopastoralism takes place (Bernués et al. 2005, Beilin et al. 2014), as well as the role played by the European Common Agricultural Policy (CAP) in this farm intensification (Matthews et al. 2006, Bernués et al. 2011, Navarro and López-Bao 2018). Moreover, a key factor in the abandonment of silvopastoral systems is their low economic competitiveness, attributed to their limited production potential and the challenges associated with mechanization, resulting in a high demand for labor, rendering them less attractive compared to more specialized systems (Plieninger et al. 2015, García de Jalón et al. 2018).

Silvopastoral practices have been associated with a number of challenges that may hinder building common productive coherence between forest management and livestock grazing (Aubron et al. 2013). Specifically, the attitudes, opinions, and objectives of both forest managers and livestock farmers shape their willingness to cooperate in joint silvopastoral management (Varela et al. 2022) while the interest of farmers in woodland forage varies with their capacity to access other crop and forage resources (Rapey et al. 2001, Aubron et al. 2013). Although these studies shed light on the existence of multiple intertwined biophysical, socioeconomic, institutional, and technical factors influencing forest grazing, the understanding from a broader social-ecological perspective on their relationships remains unclear. Therefore, integrating the knowledge of relevant stakeholders involved in silvopastoral systems on the assessment

[1]Institute of Agrifood Research and Technology (IRTA), Caldes de Montbui (Barcelona), Spain, [2]Department of Agricultural Sciences and Natural Environment, University of Zaragoza, Zaragoza, Spain, [3]Agrifood Institute of Aragon– IA2, University of Zaragoza-CITA, Zaragoza, Spain, [4]Wageningen University, Environmental Systems Analysis Group, Wageningen, The Netherlands, [5]Department of Agricultural Economics and Rural Development, University of Göttingen, Göttingen, Germany, [6]European Forest Institute. Governance Programme, Bonn, Germany, [7]Forest Science and Technology Centre of Catalonia (CTFC), Solsona (Lleida), Spain

of the influence of the different factors and their interactions at multiple scales could support effective decision making and policies to promote silvopastoralism (Hartel and Plieninger 2014, Plieninger et al. 2015).

Fuzzy Cognitive Mapping is a systems approach that can help to unravel the complexity of silvopastoralism in Mediterranean mid-mountain areas because it allows to capture and structure the knowledge of stakeholders in a graph-based representation of a complex system (Özesmi and Özesmi 2004). The resulting Fuzzy Cognitive Map (FCM) is formed by concepts describing key factors of the systems connected with directed and weighted arrows reflecting the relationships among them (Kok 2009). This semi-quantitative method allows to improve the understanding of complex and multifaceted systems where available information is scarce or vague (Jetter and Kok 2014) and has been previously used to analyze complex issues such as the effect of forest management on the provision of ecosystem services (Ladu et al. 2020, Eriksson et al. 2023), the influence of external changes on pastoral households (Easdale and Aguiar 2018), the process of landscape change in Europe (Van der Sluis et al. 2018), or the evaluation of agricultural policies (Christen et al. 2015). To the best of our knowledge, this is the first time FCMs are used to represent and explore the factors influencing forest grazing.

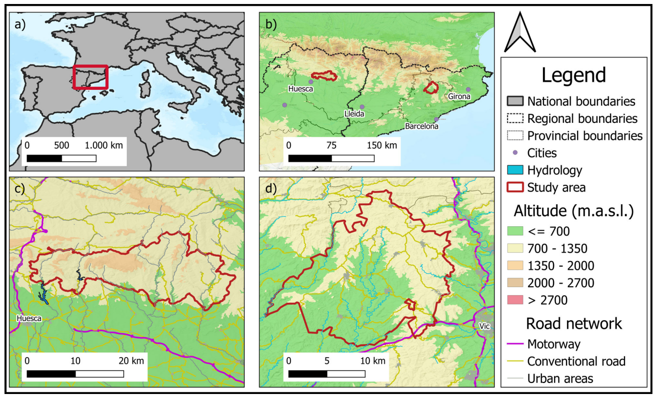
With this study we aim to analyze the shared understanding of stakeholders on the factors that drive silvopastoralism in Mediterranean mid-mountain areas, in order to identify key policy implications to promote and support this traditional multiple land use practice. We refer to silvopastoralism as a land use system where forest grazing is the main management activity that defines these systems and it is required to ensure their continuity (Bugalho et al. 2011) and that our work intends to investigate. We specifically (1) identified and characterized the factors influencing forest grazing in the Mediterranean; (2) analyzed the relationship between the factors through participatory Fuzzy Cognitive Mapping in two contrasting case studies in Spain: Sierra de Guara Natural Park and Lluçanès region; (3) investigated the relative impact of feedback relationships and external drivers in these systems. The success of silvopastoral management systems requires a shared understanding between forest owners, livestock farmers, and potentially enabling actors such as technicians from different public administrations (Guerin et al. 2010, Varela et al. 2022). Our study employs FCMs to integrate the shared view of these stakeholders on silvopastoralism. FCMs enable modeling and comparing the dynamic behavior of such complex systems as perceived by these actors. Importantly, this paper adds methodological innovations to the traditional FCM metrics, proposing and applying novel post-processing analyses to improve the understanding of FCM dynamics.

METHODS

Case study description

The study was conducted in Mediterranean mid-mountain areas located in the pre-Pyrenees (north-eastern of Spain; Fig. 1a, b) in two regional case studies: Sierra de Guara Natural Park (Guara) and Lluçanès. As in the rest of the Mediterranean basin, the diversity of ecosystems resulting from a complex topography and multiple microclimates was enriched by cultural land use

Fig. 1. Location of the case study areas of Guara and Lluçanès.



systems (MacDonald et al. 2000, Casals et al. 2009, Olaizola et al. 2015). Farming (especially livestock farming through grazing) and forest management contributed to shaping a mosaic landscape with high cultural and biological values. These traditional and multifunctional management systems are, however, prone to either abandonment or intensification.

Guara is a rugged protected area involving 15 municipalities in the province of Huesca (Fig. 1c), comprising 81,491 ha (Natural Park and Peripheral Protection Zone). The forest is mostly publicly owned (60%) and is usually used for forage, firewood, mushroom picking, and hunting games. Livestock family farming has traditionally been the main livelihood activity in Guara, although the number of livestock heads has decreased dramatically during the last decades while other economic activities, mainly tourism, have increased (Olaizola et al. 2015). In 2019, in Guara, there were 143 sheep farms with a total of 51,242 heads, and 80 cattle farms with a total of 2462 heads (Gobierno de Aragón 2019).

Lluçanès comprises 13 municipalities in the province of Barcelona (Catalonia) and extends over 40,000 ha in an altitudinal range between 380 m and 1200 m (Fig. 1d). Forestry and farming are key economic activities in the region and strongly integrated into the family farm, although these have undergone a radical transformation in the last decades. The low economic profitability of forests is leading to their lack of management. Simultaneously, farming systems have decreased the number of small farms and intensified, increasing the number of animals per farm as well as their land. In 2019 there were 60 sheep farms with a total of 20,245 heads, and 191 cattle farms with a total of 29,000 heads (GENCAT 2019). Nowadays, different initiatives and governance systems to facilitate collaborative processes between forest owners and pastoralists are emerging to support forest grazing aiming at reducing wildfire hazards in the region (Capdevila et al. 2021).

Fuzzy Cognitive Mapping

Fuzzy Cognitive Mapping enables structuring of the opinion of individuals and groups in a graph-based representation of a complex system that includes the interactions and feedbacks between the components (Kok 2009). FCMs intend to represent the shared belief system of a group of people and can be constructed either by aggregating multiple individual FCMs (Özesmi and Özesmi 2004, Knox et al. 2023) or by constructing a shared FCM in a participatory workshop setting (Diniz et al. 2015). The latter is the methodological approach selected in this work because the interaction between participants provides opportunities for discussion, deliberation, negotiation, and consensus building, offering a more coherent and comprehensive view of the system (Jetter and Kok 2014, Hamilton et al. 2022). Nevertheless, the methodologies for aggregating multiple individual FCMs are constantly evolving (Knox et al. 2023).

The graphical structure of the FCM is composed of concepts (Ci) representing the factors of the system and, ranging between 0 and 1, joined by directed arrows or connections representing the relationships between concepts ($C_i \rightarrow C_j$; Kosko 1986). FCM further functions as a semi-quantitative conceptual model that can be applied in futures studies, scenario planning, and complex systems modeling (Jetter and Kok 2014, Voinov et al. 2018). FCM operates with four main components: the state values of concept i in the iteration k (A^k_i), the adjacent matrix containing the weight wij ∈ [−1, 1] assigned to each pair of concepts (Ci, Cj), the activation vector that defines the initial configuration (k=0) and the transfer function (i.e., sigmoidal or logistic) that normalize the output to a predefined interval (Felix et al. 2019). Because the updated concepts in our model are influenced by other concepts (Felix et al. 2019), we applied Kosko's activation rule (Kosko 1986) to produce a new state vector at each iteration until a stop condition is met:

$$A_i^{(k+1)} = f\left(\sum_{j=1;i\neq j}^{N} w_{ij}\, A_j^{(k)}\right) \quad (1)$$

Although the values of factors can "implode," "explode," reach cyclical stabilization, or stabilize after multiple iterations (Kok 2009), stabilization is often desirable because it results in consistent responses, enabling experts to better understand the system's behavior (Felix et al. 2019). Our approach to model stakeholders' perceptions on the social-ecological dynamics of forest grazing in Guara and Lluçanès Mediterranean mid-mountain silvopastoral systems study cases builds on five main steps (Table 1).

Identification of forest grazing factors
A first inquiry on the potential factors relevant to the implementation of forest grazing was compiled from a literature review and the information collected in the frame of a research project on silvopastoralism conducted in the area (Varela et al. 2022). The preliminary list of factors was discussed, grouped, and revised through online semi-structured interviews with eight experts with diverse backgrounds, and relevant knowledge and management expertise on silvopastoral systems in November 2021. The factors were grouped into five categories: social, technological, economic, environmental, and institutional to facilitate their identification. The list of these preliminary factors is provided in Appendix 1 (Table 1A). Forest grazing was established as the central factor while the remaining served to determine the model boundaries (Jetter and Kok 2014). Finally, a set of factors were named and defined that served as a starting point for the FCM development in the workshops with stakeholders.

Table 1. Description of steps and methods followed.

Step	Description	Method
i	Identification of forest grazing factors	Literature review, previous project knowledge, and semi-structured interviews with researchers (n = 8)
ii	Elicit experts' knowledge of forest grazing	Workshops with stakeholders (9 and 8 participants): Fuzzy Cognitive Mapping
iii	Adjust, calibrate, and validate the models	Matrix
iv	Explore the structure and behavior of forest grazing system as perceived by stakeholders	Structural analysis and loop dominance analysis
v	Analyze the relative impact of driver change on the behavior of the system	Sensitivity analysis

Participatory workshops for FCM building
We followed the method proposed by Gramberger et al. (2015) for stakeholder identification and selection. We distinguished four relevant groups of stakeholders, namely, forest owners and managers, livestock farmers, environmentalists, and technicians working in the public administration at regional, provincial, or county levels. Then, we settled a quota of one participant within each category, and two individuals fitting these characteristics were invited to participate in the study to ensure a balanced representation of all stakeholders' perspectives while maintaining manageable group dynamics for effective interaction and discussion (Jetter and Kok 2014). The number of participants in our study falls within the range of 6 to 15 participants, consistent with other FCM studies conducted through participatory workshops (i.e., van Vliet et al. 2010 with 7 participants; Gray et al. 2015 with 15 participants; Penn et al. 2013 and Ahmed et al. 2018 with 11 participants; Henly-Shepard et al. 2015 with between 6 and 15 participants). A four-hour deliberative workshop was held in each case study where stakeholders met, debated, and negotiated to agree on a shared map that merges their perceptions on forest grazing. The workshop in Guara was held in November 2021 and involved 9 participants while in Lluçanès it took place in May 2022 and was attended by 8 participants. In Guara, participants included representatives from regional government, the Natural Park, environmental organizations, and the leaders of farmers' associations. In Lluçanès, participants ranged from technicians at provincial and county-level administrations to environmental agents, as well as heads of both forest owners' and farmers' associations. Workshops were guided by three facilitators and audio was recorded with the participants' permission. Prior to the workshops, the preliminary list of factors selected by the group of experts and their definitions was sent to the participants.

The workshops consisted of four phases, starting with a knowledge activation phase where the predefined factors and their descriptions were provided on printed cards and discussed with participants to ensure understanding while allowing them to add, change, or remove factors (Jetter and Kok 2014). In the second phase, we introduced the logic of causal connections providing some examples of positive and negative causal links and mapped the relationships among the factors accordingly. Following the stakeholders' discussion, facilitators drew the agreed relationships on a flipchart using directed arrows colored in blue to designate positive causality and red for negative ones. In the third phase, respondents identified the five most important connections of each sign. At the end of the workshop, we analyzed the structure of the FCM, discussed the role of each factor, and explored the dynamic behavior of the system with the participants. Information on how participants expect the system to behave dynamically was collected during the workshop by asking "what if" questions to the participants. In this process, a weight of 0.5 was given to all relationships between factors while changing the initial value of drivers in a pilot FCM to simulate the "what if" effect using Mental Modeller software (Gray et al. 2013).

FCMs post-processing: adjustment and calibration

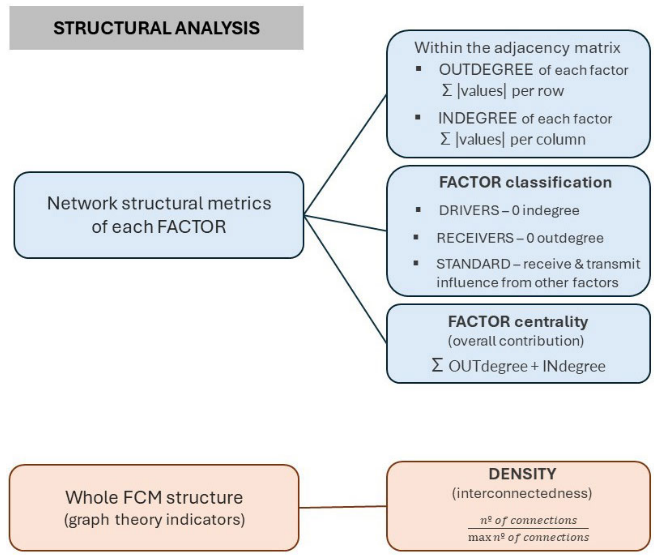
The post-processing involved the adjustment and calibration of the maps crafted by stakeholders during the workshops to enable proper FCM computation and meaningful interpretations of the dynamics of the system (Jetter and Kok 2014). This process is described in detail in Appendix 1. First, we adjusted the model by removing redundancies and relationships with very different timeframes (Fig. 1A). We used a qualitative scale of three items to weight the relationships guided by common practices in FCM studies (Özesmi and Özesmi 2004, Penn et al. 2013). Specifically, we assigned values of 0.8, 0.5, or 0.2 to represent high, moderate, or low levels of influence in the relationships based on a combination of participants' collective agreement during the workshop and their individual selection in the feedback. These values were chosen based on previous experiences with developing FCMs (Özesmi and Özesmi 2004, Penn et al. 2013). Then, we conducted the dynamic modeling without using any transformation function, hence allowing the concept values to be flexible rather than restricted to a predefined interval (Gray et al. 2015, Edwards et al. 2023). The activation function was implemented by including a self-reinforcing connection for drivers, with a static value of +1 and an initial value of 0.9, while other concepts were initialized to 0 (Diniz et al. 2015). Drivers represent external forces influencing the performance of the system and serve as a starting point for calibration (Kok 2009). Specifically, the activation function simulates a static influence of drivers within the system and a baseline state for the remaining factor, which enabled us to quantify and compare the influence exerted by both feedback loops and drivers during the subsequent loop dominance and sensitivity analyses, respectively (Kok 2009).

The calibration consisted of fine-tuning the relationships of the model to enhance its capacity to capture stakeholders' perspectives and describe the dynamic behavior of the system, thereby providing valuable insights for decision making (Jetter and Kok 2014). Based on the feedback gathered during the fourth phase of the workshops (Diniz et al. 2015) and supported with scientific literature, the values of weights in the models were re-adjusted (Table 2A and Table 3A) to accurately capture the stakeholders' understanding of forest grazing in the case studies (Figs. 2A and 3A) while minimizing the authors' contribution in the co-production process (Diniz et al. 2015, Olazabal et al. 2018, Edwards and Kok 2021, Edwards et al. 2023).

Structure analysis

FuzzyDANCES software (Groot et al. 2012 as cited in Aravindakshan et al. 2021, Alomia-Hinojosa et al. 2023, Edwards et al. 2023) was used for analyzing each FCM (Fig. 2). First, outdegree and indegree were estimated as the sum of the absolute

Fig. 2. Network structural metrics estimated in each factor and Fuzzy Cognitive Map.



values of the weights of outgoing connections and ingoing connections, respectively, and factors were classified as drivers, receivers, or standard. The centrality of each factor was calculated as an indicator of its overall contribution to the FCM (Özesmi and Özesmi 2004). Then network structural metrics of each FCM were estimated using graph theory indicators.

Second, loop dominance analysis helps to further explore the relationship between the model structure and its behavior (Schoenberg et al. 2020). Feedback loops are a key characteristic of FCM that entail circular casual relationships where (a part of) the outputs produced by a factor return as input of the same factor, leading to nonlinear dynamics and emergent behavior of the system (Kok 2009). FuzzyDANCES systematically identified the feedback loops in the FCM and measured the magnitude of the output produced by each feedback loop (loop score) by multiplying the weights of the relationships involved in the loop. Then the scores of the loops within each FCM were added to obtain the net score of the system that served to estimate the relative influence of each loop. Positive feedback loops reinforce or amplify the output of the factor leading to exponential growth in the system whereas negative feedbacks loops reduce the output, leading to stability or equilibrium in the system (Schoenberg et al. 2020, Hamilton et al. 2022).

Sensitivity analysis

A sensitivity analysis was performed (and it is necessary) to assess the robustness of the models by exploring the impact of changes in drivers' values on the behavior of the system. We used the winding stairs algorithm based on the Monte Carlo sensitivity analysis (Jansen et al. 1994, Chan et al. 2000) in FuzzyDANCES performing 1000 windings per driver (Edwards et al. 2023). The drivers were varied with a multiplication factor settled between 0.5 and 1. Finally, linear regression analyses were estimated to relate the values of each dependent variable (factors) with the independent variables (drivers) and both regression coefficients

Table 2. Factors preselected and adapted by stakeholders in the workshops.

Group	Nº	Factors	Guara	Lluçanès
Focal factor	CO	Forest grazing: Land-use type where livestock grazes on scrublands and woodlands providing forage, shelter, and resting places.	x	x
Social	C1	Agricultural abandonment: Decline of livestock farming and forestry activities due to the reduction in the number of farms.	x	x
	C2	Sector attractiveness: Generational turnover and socioeconomic motivation in adopting a livelihood based on farming and forestry.	x	x
	C3	New entrants: Process of incorporation of new landless professionals to farming or related land-based business.	-	x
	C4[†]	Environmental concern: Social interest toward environmental protection and animal welfare.	x	x
Technological	C5	Farm diversification: Livelihood strategy of households that allocate their resources (mainly labor) to other on-farm or off-farm economic activities.	x	-
	C6	Organization of the sector: Capacity of farmers and forest owners to associate in formal organizations for defending their collective interests.	x	x
	C7	Difficulties of forest grazing: Workload increase for livestock management in the forest due to the steep slopes, ownership structure, and interactions with wildlife and tourists.	x	x
	C8	Infrastructure for grazing: Availability of facilities to access and handling animals in forest areas (paths, fences, water points, shelters).	x	x
	C9	Technology and innovation: Development of new tools and knowledge for the sector (i.e., GPS collars, drones, Lidar, machinery).	x	x
	C10	Forest management: Spatial-temporal planning of interventions (harvesting, clearing, prescribed fire) and uses (recreational, hunting, grazing) to ensure multifunctionality.	x	x
Economic	C11	Gap in prices: Difference between the prices received by farmers and forest owners and the prices they pay for inputs (fuels, fertilizers, concentrates, etc.), labor, and machinery.	x	x
	C12	Other economic activities: Presence in the territory of other land uses, activities (tourism, industry) or livestock farming models (intensive pig and cattle fattening).	x	-
	C13	Raid horse breeding: Economic activities mainly promoted by sheikhs from the United Arab Emirates who buy farms at high prices for the breeding of thoroughbred racehorses for equestrian raid competition.	-	x
	C14	Pork industry: Existence in the territory of intensive pig production and fattening systems.	-	x
	C15	Access to land: Farmer possibilities to acquire or expand the territorial base of their farm.	x	x
Environmental	C16	Climate change: Modification of the rainfall regime, increase in temperature, and frequency of extreme events.	x	x
	C17	Wild and feral fauna: Species that live and reproduce in the territory, including game species.		x
	C18	Wildfire hazard: Vulnerability of the forest area because of its composition and structure, to ignition and uncontrolled spread of fire.	x	x
	C19	Pests and diseases: Proliferation of harming organisms affecting livestock and forest productivity.	x	x
	C20[‡]	Forest expansion: Increase of the forest due to both densification and colonization of woody vegetation on agricultural lands.	x	x
Political or Institutional	C21	Common Agricultural Policy (CAP): Subsidies of the main EU agricultural policy including direct payments to farmers and rural development funds (PDR).	x	x
	C22	Environmental policies: Land use regulations aimed at the protection of biodiversity, environmental conservation, and sustainable development (Natura 2000 Network, Forestry Law, etc.),	x	-
	C23	Access to funding: Possibility of acquiring economic resources to undertake, invest, or expand activities and projects in the forestry and livestock sector.	-	x

[†] The concept of environmental concern (C4) in Lluçanès was renamed as environmental knowledge and education to differentiate it from extreme environmental issues and underline the importance of social education to take action for the environment by supporting sustainable management.
[‡] The concept of forest expansion (C20) in Lluçanès was renamed as forest densification to stress that changes in the regional forest area were mainly caused by increasing vegetation in existing forest areas rather than shrub encroachment in agricultural land.

and coefficient of determination (R^2) were used, respectively, to quantify the strength of the influence of changes on target variables and to assess the contribution of the drivers' changes to the variation of the output through the total sensitivity index (TSI; Chan et al. 2000, Alomia-Hinojosa et al. 2023).

RESULTS

Factors influencing forest grazing in the Mediterranean

Preliminary interviews with experts yielded a set of 19 factors influencing forest grazing in the Mediterranean. Most of them were used to build the FCM although slight changes were made during the workshops (Table 2). Participants in Guara agreed to include a new factor called 'farm diversification'. Participants in Lluçanès added two new factors named 'new entrants' and 'access to funding'. They also split other economic activities into raid horse breeding (a racehorse discipline that consists of long-distance races) and pork industry. Furthermore, they renamed environmental concern as knowledge and education and forest expansion as forest densification. Finally, they excluded environmental policies. The FCMs were formed by 20 factors in Guara and 21 in Lluçanès, respectively.

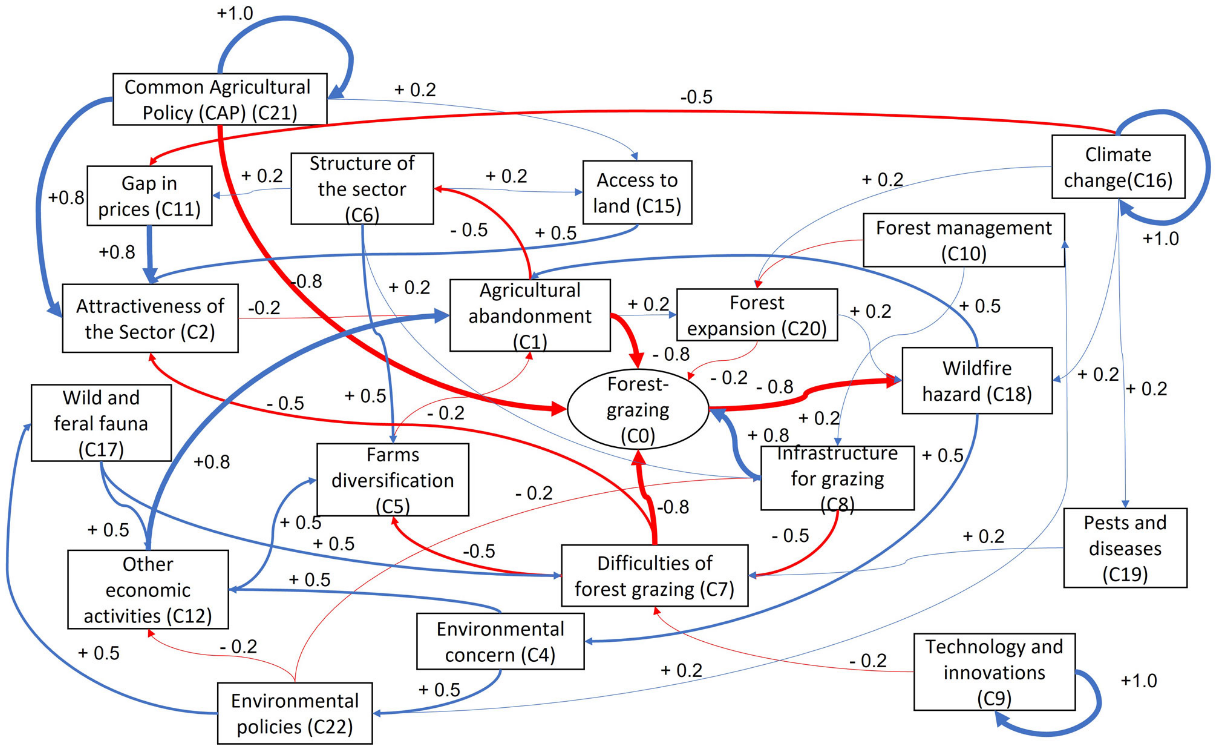
Table 3. Comparison of metric characteristics of the Fuzzy Cognitive Maps (FCMs).

Indicator	FCM Guara	FCM Lluçanès
Number of factors	20	21
Number of connections	40	45
Density	0.118	0.119
Number of driver factors	3	5
Number of receiver factors	0	0
Number of ordinary factors	17	16

Perception of the relationships among factors

Graph theory indicators showed a similar density of the maps, although the FCM in Lluçanès had a slightly higher number of factors, connections, and drivers (Table 3). The FCM in Guara consisted of 20 factors, 40 connections, and showed 3 drivers whereas the FCM in Lluçanès comprised 21 factors, 45 connections, and presented 5 drivers. Figures 3 and 4 show the post-processed FCM built by stakeholders in the Guara and Lluçanès workshops, respectively. These FCMs represent the

Fig. 3. Fuzzy Cognitive Map for forest grazing in Guara. The thickness of arrows and numbers denotes the weight of the influences between factors where red indicates negative relationships and blue indicates positive relationships.



shared perception of stakeholders about forest grazing in each case study. Key drivers and the most influential or central variables are summarized in Figure 5. Society's knowledge and environmental education and other economic activities in the territory were key drivers unique to Lluçanès while CAP and climate change were common key drivers in both case studies. Forest grazing and the socioeconomic attractiveness of the sector were the most influential or central variables in both Guara and Lluçanès, while reduction in the number of farms was a central variable in the former and access to land in the latter (Fig. 4A and Fig. 5A). The main output of forest grazing in both FCMs was the reduction of wildfire hazard (C18).

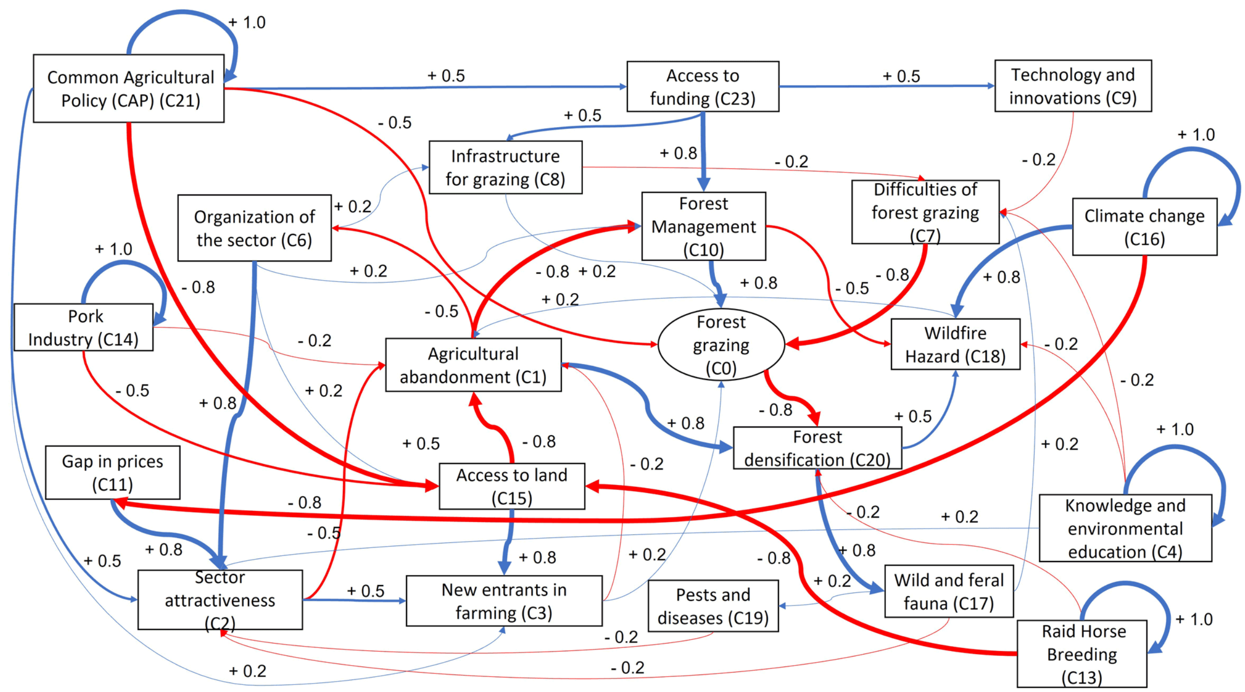
The participants in Guara acknowledged the role of environmental policies, especially those from the Natural Park in favoring the conservation of wild flora and fauna (C17), reducing the pressures of human activities by restricting the creation of new infrastructure for grazing such as roads or tracks (C8), and promoting forest management practices for conservation (C10). In contrast, in Lluçanès, environmental policies were not considered by participants, thus other economic activities, raid horse breeding (C13) and the pork industry (C14) exerted a strong influence on the system, especially by reducing access to land (C15). Agricultural abandonment was reduced by the attractiveness of the sector in both FCM, but while farm diversification negatively influenced agricultural abandonment in Guara, the pork industry and access to land contributed to reducing abandonment in Lluçanès.

In both case studies, stakeholders identified climate change as a factor that decreases the gap between input and output prices (C11), resulting in lower revenues and increasing wildfire hazard (C18). Technology and innovations (C9) were also recognized for reducing the difficulties of forest grazing. Moreover, stakeholders in the two case studies identified a positive relationship between the CAP and the attractiveness of the sector (C2) as well as a negative relationship between the CAP and forest grazing, the latter mainly due to the pasture eligibility coefficient of the CAP 2014-20, that penalized woodlands in order to perceive the basic payment scheme. However, the most striking difference when comparing the two FCMs was related to the impact of CAP on access to land. Whereas stakeholders in Guara considered a medium and positive weight arguing that "The economic assistance of CAP supports young and beginning farmers to access land," in Lluçanès stakeholders rated a high and negative weight to this connection because they interpreted that "the basic payment scheme (CAP 2014–2020) based on surface area increases land demand among livestock farmers thus increasing land price."

Feedback loops influencing system behavior

Loop dominance analysis revealed 67 feedback loops in Guara that exert a net score in the system of 0.720 and two loops explaining 62% of the changes in the dynamic behavior of the system (Table 4A). The most important loop explained 44% of the behavior and showed the self-reinforcing performance of agricultural abandonment (C1), leading to a reduction of forest

Fig. 4. Fuzzy Cognitive Map for forest grazing in Lluçanès. The thickness of arrows and numbers denotes the weight of the causal effect influences between factors where red symbolizes negative relationships and blue indicates positive relationships.



grazing that contributed to increased wildfire hazard (C18) that ultimately produced more agricultural abandonment, i.e., increased wildfire hazard reduces the availability of grazing surfaces and therefore contributes to the abandonment of agricultural systems. The second most influential loop also involved agricultural abandonment, which led to reduced forest grazing and increased wildfire hazard that in turn increased the environmental concern of society (C4), and the presence of other economic activities (i.e., tourism; C12) that contributed to agricultural abandonment. Specifically, stakeholders in Guara argued that the risk of fires increased social concern about environmental issues, while this concern and sensitivity for the environment also increase the social demand for open spaces and tourism.

In Lluçanès, we identified 38 feedback loops with a net score of 0.605 and 4 loops explaining 57% of the dynamics (Table 5A). The most important loop explained 17% of the dynamics and showed that forest grazing reduced forest expansion or densification (C20), which in turn decreased the populations of some species of wild and feral fauna, reducing the difficulties for and in turn increasing forest grazing. Another three loops explained 13% of the dynamics each of them; they all involved agricultural abandonment as a trigger either by reducing the organization of the sector (C6) and its attractiveness (C2) or by reducing forest management (C10) and increasing wildfire hazard (C18) or by increasing forest expansion (C20) and wildfire hazard (C18).

Current situation of forest grazing in case studies

In Guara, the steady state obtained by the iterative multiplication of the state vector and adjacent matrix showed a strong decline in forest grazing reaching the lowest values of all factors in the model (Fig. 6). Wildfire hazard obtained the highest value followed by agricultural abandonment whereas forest expansion, access to land, and sector attractiveness showed low but positive scores as well.

The dynamic model for Lluçanès also reflected a rapid increase in wildfire hazard and forest expansion being the factors that scored higher on the map (Fig. 7). Forest grazing was also negative as in Guara, although absolute values were closer to zero. New entrants in farming and especially access to land stabilized at the lowest level in the system.

Effects of drivers on forest grazing

We explored the dynamics of FCMs with sensitivity analysis to further understand how the system responds to change. The sensitivity analysis assesses the relative change of the factors under the evolution of drivers, thus, providing key insights into the role of these drivers, which represent external processes, in influencing the steady state of the systems (Kok 2009, Alomia-Hinojosa et al. 2023). Figures 8 and 9 show the response of forest grazing to the influence of drivers in Guara and Lluçanès, respectively, while the response of the remaining factors is reported in Appendix 1 (Table 6A and Table 7A). According to stakeholders' perception, technology, and innovations in Guara and knowledge and environmental education in Lluçanès would promote forest grazing while the remaining drivers would have negative effects. The driver that would most negatively influence forest grazing in Guara was the CAP, while in Lluçanès that role was played by climate change, although the latter also has a negative effect in Guara. Forest grazing was also sensitive to other economic activities in Lluçanès, with a greater negative effect

Fig. 5. Summary highlighting the main differentiating characteristics of Fuzzy Cognitive Map in Guara and Lluçanès.

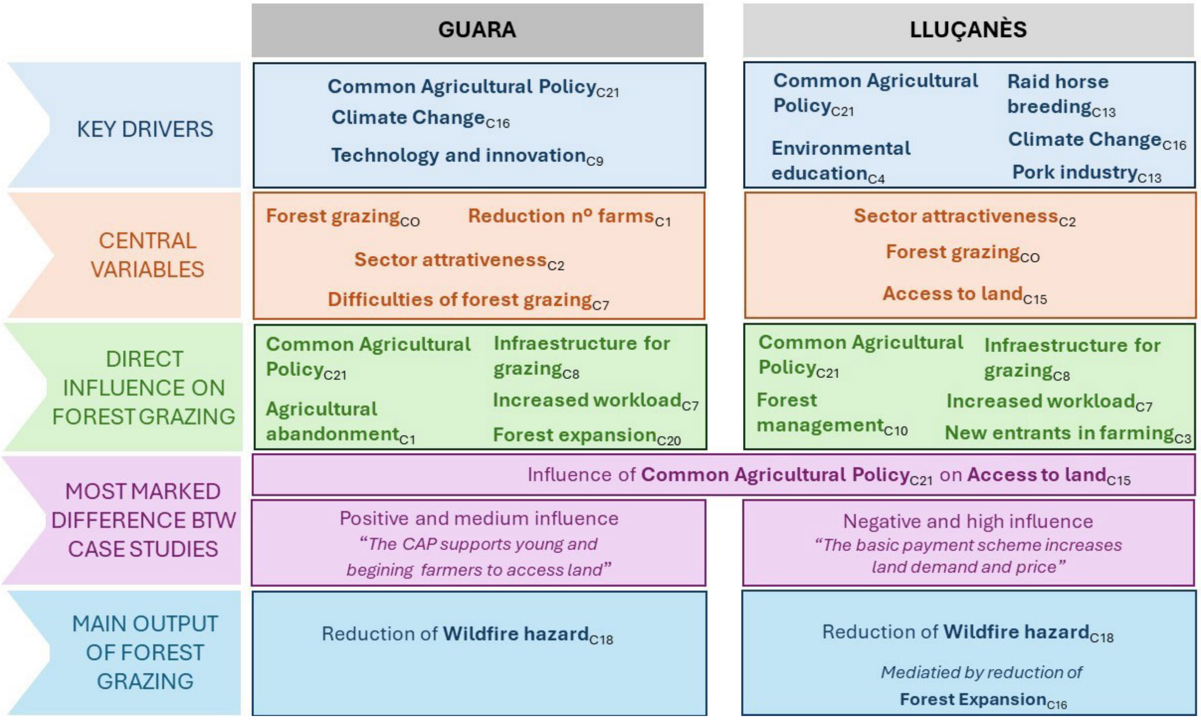


Fig. 6. Dynamic output from the Fuzzy Cognitive Map in Guara reflecting the current situation. X-axis represents the number of iterations and Y-axis the value of the factors.

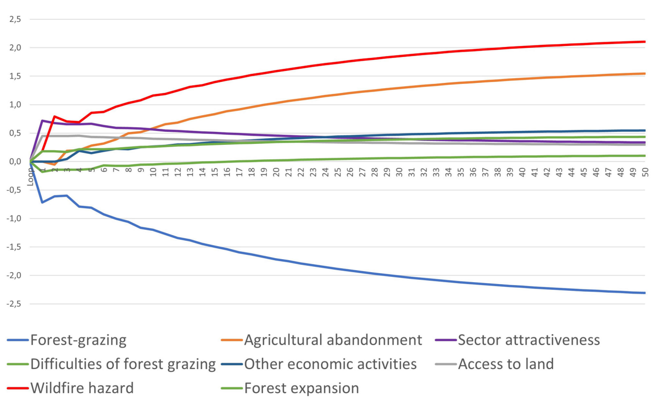
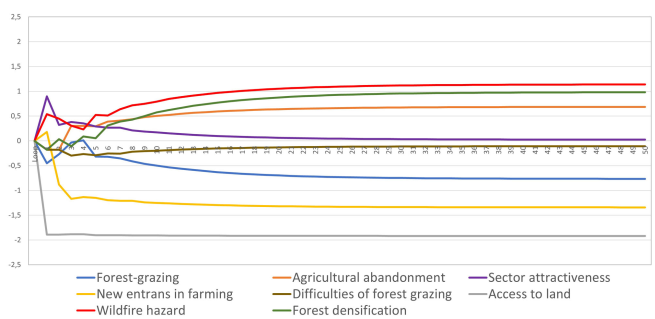


Fig. 7. Dynamic output from the Fuzzy Cognitive Map in Lluçanès reflecting the current situation. X-axis represents the number of iterations and Y-axis the value of the factors.



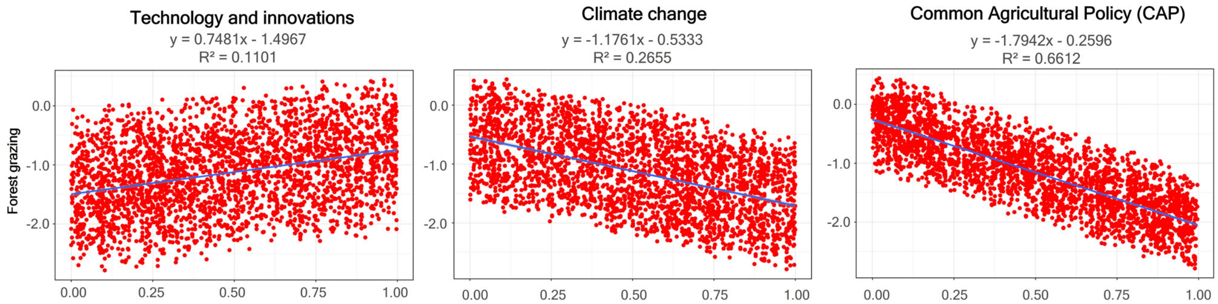
produced by raid horse breeding than by the pork industry. R^2 should be interpreted in relative terms as indicators of the influence of the drivers in the factors. Lower values of R indicate no relevant relationship, but could also suggest that the model exhibits nonlinear behavior (Chan et al. 2000): Values of R^2 close to zero (< 0.1) such as the CAP or pork industry in Lluçanès, are also of specific interest because they hint toward concepts that have either no observable influence or that have strong influence but in opposite directions, therefore having little influence when added.

DISCUSSION

Factors and dynamics of silvopastoralism in Mediterranean mid-mountain areas

The dynamic output of the FCM in Guara and Lluçanès shows a marked decline in forest grazing, especially in Guara, leading in both cases to a strong increase in wildfire hazard (Mosquera-Losada et al. 2018), the main environmental function recognized by stakeholders in both regions. In the case of Lluçanès, the factors that scored lowest in the dynamic output were access to land and new entrants, with the former showing also a high centrality. Although access to land is essential for the viability of pastoral systems, the inclusion of new entrants as a new factor in Lluçanès highlights the additional challenge posed by the lack of

Fig. 8. Sensitivity analysis of the regression relationships between drivers and forest grazing in Guara.

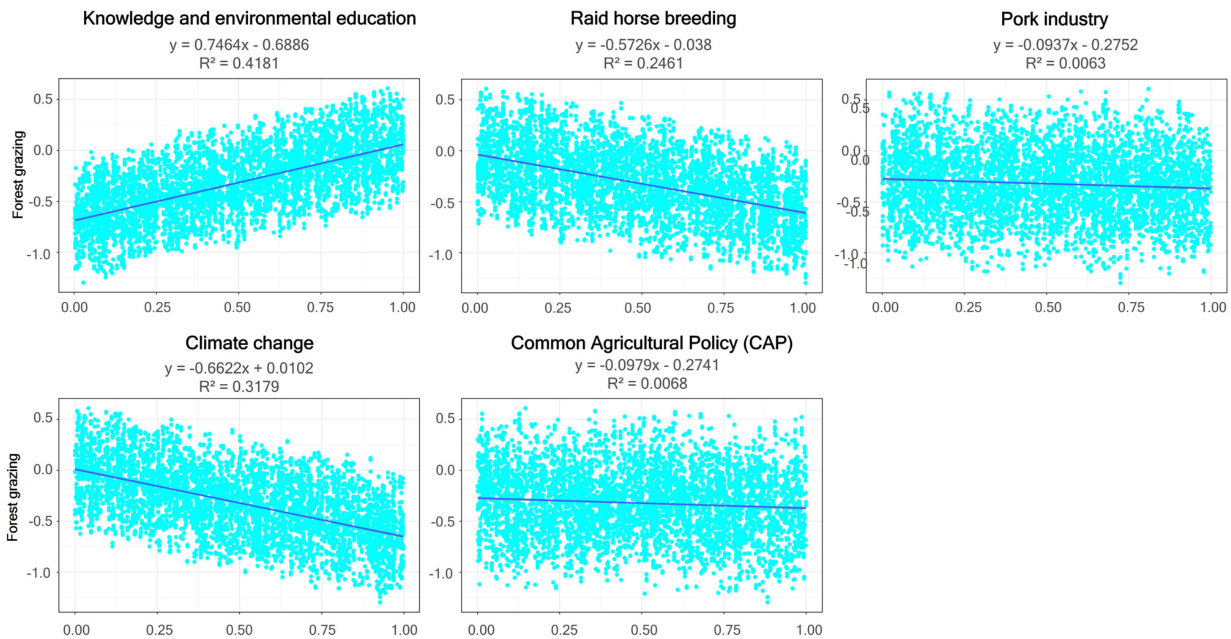


an agrarian family tradition for accessing land (Góngora et al. 2019). In contrast, access to land was not a relevant factor in Guara because the context of agricultural abandonment is more pronounced as shown by the high centrality obtained by this factor. The decline in the number of livestock farms in the Mediterranean has been a prevalent issue in sheep farming systems, especially in recent years mainly because of the high labor requirements and low socioeconomic attractiveness (Olaizola et al. 2015, Paas et al. 2021). Farm abandonment was involved in most of the dominant feedback loops in both systems triggering forest expansion and wildfire vulnerability, exacerbating the challenges faced by farmers and leading to more abandonment (Moreira et al. 2011, van der Zanden et al. 2017). However, we found that the net influence produced by these loops was slightly higher in Guara than in Lluçanès. Because positive feedback loops reinforce or amplify the output of the factor leading to exponential growth in the system (Schoenberg et al. 2020, Hamilton et al. 2022), the greater amplifying effect found in Guara suggests that a small disturbance could trigger exponential changes in the system's behavior (Schoenberg et al. 2020, Hamilton et al. 2022), such as the perceived undesirable decline of sheep farming systems in this region (Paas et al. 2021) that reduces forest grazing (Varela et al. 2022).

The sector attractiveness resulted in a high central factor in both FCMs, influenced in both cases by the margin between input-output prices because the continuous decline of revenues in pasture-based livestock systems threatens the generational turnover and continuity of forest grazing in the Mediterranean (Bernués et al. 2011). The high opportunity cost of farm assets (i.e., labor and land) and the increasing higher-paying job opportunities from other activities in the territory are pivotal in the decline of pastoral systems, such as silvopastoral systems (Bernués et al. 2011, Góngora et al. 2019). However, our work reflects different regional patterns in the perceived role that other economic activities may play in the continuation of pasture-based livestock farming. In Guara, the role of other economic activities (namely tourism) was considered positively influencing farm diversification and in turn, reducing agricultural abandonment. Diversification of labor beyond on-farm activities is a widely adopted strategy in extensive livestock systems (Lecegui et al. 2022b). Conversely, in Lluçanès these other economic activities were explicitly reflected through two factors: raid horse breeding and pork industry, acknowledging the importance of the latter in Catalonia, the main pig-producing region in Spain (while the country itself accounts for 22% of EU pig production; MAPA 2023). Both were perceived to decrease land availability, increasing the land price and the difficulties for silvopastoralism in Lluçanès. The role played by labor diversification beyond on-farm activities and by other economic activities may vary depending on the policy and governance framework (García-Martínez et al. 2009) because they may create economic opportunities and improve the financial performance, being crucial for maintaining livestock farming systems (Olaizola et al. 2015) while competing for land or labor and ultimately contributing to their displacement (Bernués et al. 2011, Muñoz-Ulecia et al. 2021).

Infrastructures and active forest management were the main factors directly and positively influencing forest grazing in both regions, pointed out as determining factors in the use of mountain pastures (Esgalhado et al. 2024). However, the main perceived barriers to forest grazing were the associated difficulties and workload, which align with previous findings in the literature (Varela et al. 2022). The inclusion of the factor access to funding in Lluçanès acknowledged the regional initiatives to reduce wildfire risk by decreasing the encroachment of vegetation, facilitating livestock access to the forest, and providing water points (Capdevila et al. 2021). Reducing the difficulties of forest grazing through financing reinforced the feedback loop identified in Lluçanès toward increased forest grazing. This suggests that structural deficiencies are relatively easy obstacles to overcome through stakeholders' collaboration and reliable financial support (Hernández-Morcillo et al. 2018, Varela et al. 2022). The difficulties of forest grazing attained a high centrality in Guara; however, stakeholders in both FCMs recognized the development of technology and innovations such as GPS or virtual fencing to reduce these difficulties by improving productivity, profitability, and the quality of life of farmers (Sunding and Zilberman 2001, Paas et al. 2021, Horn and Isselstein 2022), being considered in Guara as a driver promoting forest grazing while in Lluçanès they were influenced by the access to funding. Despite grazing practices playing a vital role in maintaining certain target habitats and species in protected areas (Halada et al. 2011), our study shows that some environmental policies can create additional challenges because of the coexistence with wildlife, recreational users in the forest, or the restriction of certain types of infrastructure, thus hindering forest grazing and reducing its effectiveness in promoting biodiversity and ecosystem services (Lecina-Diaz et al. 2019).

Fig. 9. Sensitivity analysis of the regression relationships between drivers and forest grazing in Lluçanès.



Influence of exogenous drivers on silvopastoralism

Besides the internal dynamics described above, forest grazing is also shaped by exogenous factors that drive the system. The sensitivity analysis revealed that the Common Agricultural Policy (CAP) and climate change are the major drivers limiting forest grazing in both case studies, while others such as the abovementioned pig production and raid horse breeding in Lluçanès appear to depend on the regional socioeconomic context.

The CAP has played an important role in shaping EU livestock farming systems (Guerra et al. 2016, Muñoz-Ulecia et al. 2021). Stakeholders in both case studies acknowledge that the CAP enhanced the attractiveness of the sector by providing funds that contribute to farming revenues (Pe'er et al. 2014, European Commission 2021). Despite the woody component being clearly recognized within the CAP, there is a minimal overall appreciation of agroforestry (Mosquera-Losada et al. 2018, Rodríguez-Rigueiro et al. 2021), as reinforced by our results where stakeholders agreed that forest grazing was discouraged by the CAP, as woodlands were not eligible for Pillar 1 support in the previous CAP. Moreover, we found a contrasting perception across case studies on the role played by the CAP on land access. Although the CAP is considered to facilitate access to land in Guara, the increased competition for land in Lluçanès gives rise to a detrimental perspective of the CAP because of land concentration that makes access difficult for small farmers (Paniagua 2001, Nori 2022).

Climate change poses important challenges to the sustainability of pastoral systems in the Mediterranean (Rubio and Roig 2017). However, silvopastoral systems offer opportunities for creating synergies between climate change mitigation and adaptation in the Mediterranean mid-mountain areas by maintaining mosaic landscapes that enhance carbon storage (Hernandez-Morcillo et al. 2018) and increasing resilience to wildfires (Lecina-Diaz et al. 2023).

Our results show that stakeholders' perception of the importance of drivers is contextual, with the CAP being more important in Guara and climate change in Lluçanès. Our hypothesis is that stakeholders in marginalized areas (i.e., Guara) allocate more importance to policy challenges addressing basic needs while environmental challenges are more prominent in more productive areas (Nguyen et al. 2016, Lecegui et al. 2021).

Engaging diverse and highly knowledgeable stakeholders in workshop settings provided a comprehensive understanding of the system revealing new insights into the factors, drivers, and dynamics shaping silvopastoralism in Mediterranean mid-mountain areas that may not be readily apparent when using other methods in isolation. Using FCMs shows its usefulness for knowledge coproduction and social learning (Diniz et al. 2015). A key contribution of our work is that it quantitatively depicts the magnitude of internal feedback loops and external drivers providing a more nuanced understanding of FCM (Walker et al. 2012, Dorninger et al. 2020, Hamilton et al. 2022). Because FCM development methods have become increasingly standardized, increased focus on the post-processing methods is required (Knox et al. 2023). Our work contributes to underscoring the vast potential of novel post-processing methods and metrics to gain insights into FCM outcomes.

Policy implications

The sustainability of silvopastoral systems requires coordinated policies to address their complex and multifaceted challenges. The findings from our study provide key policy implications.

Our analysis illustrates how agricultural abandonment and the decline of forest grazing practices result in increases in wildfire hazard that are intensified by climate change. Therefore, a higher integration among conservation, forest, and agricultural policies promoting forest grazing at European, national, and regional scales is highly advisable (Sandberg and Jakobsson 2018, Varela et al. 2020). The new CAP reform for the 2023–2027 period seems to be more flexible in the inclusion of wood pastures to be eligible for the Basic Income Support for Sustainability (Pillar I; Mosquera-Losada et al. 2023). A policy shift from direct payments toward the support of multifunctional farming systems, such as silvopastoral systems (Pe'er et al. 2020) and the implementation of result-based schemes for biomass reduction and wildfire prevention would lead to better outcomes for society as a whole (Varela et al. 2020, Muñoz-Ulecia et al. 2021). This is particularly justified in protected areas such as Guara, where the decline of forest grazing threatens the preservation of the environmental attributes that led to its protection. However, the design and implementation of measures to encourage environmentally beneficial practices by farmers would require a transformation of the broader governance arrangements and the structural context, ultimately building in radically different assumptions and beliefs compared to those underlying current governance arrangements as pointed out by Darnhofer et al. (2017).

At a regional level, the identified feedback loops offer room for targeted interventions that can lead to potentially transformative systemic changes by either reducing reinforcing dynamics or promoting balancing loops (Dorninger et al. 2020). Collaboration among stakeholders and financial support can contribute to overcoming structural deficiencies such as lack of fences or water points as well as shrub encroachment that hampers accessibility to herds (Hernández-Morcillo et al. 2018, Varela et al. 2022) to promote balancing and beneficial loops. Because we found that most reinforcing dynamics reducing forest grazing involve agricultural abandonment, key interventions should focus on increasing the attractiveness of the sector by facilitating access to land to young farmers (Góngora et al. 2020), particularly in Lluçanès, and by enhancing the added value of their products through the labelling of meat produced in silvopastoral systems (Lecegui et al. 2023) that could improve its economic viability. Similarly, Schaller et al. (2018) highlighted the significant potential of agricultural activities in numerous rural areas by leveraging the added value associated with the provision of public goods type services that are recognized as drivers of economic and social rural competitiveness. Beyond promoting management that increases resilience to the dynamics of fast variables, such as wildfires, targeting the relevant controlling (slow) variables such as land abandonment is required to steer these systems toward the desired direction (Walker et al. 2012). This encompasses considering threshold effects and response to external drivers (Walker et al. 2012) of key factors for triggering transformative change in silvopastoral systems.

CONCLUSION

Forest grazing in the Mediterranean is undergoing a common trajectory of decline, reducing its widely recognized role in reducing the impact of wildfires. This study contributes to the understanding of forest grazing dynamics in Mediterranean mid-mountain areas by depicting the influence of key factors, large-scale driving forces, and feedback loops in two Spanish case studies in mid-mountain Mediterranean regions.

The attractiveness of the sector was a central factor in both case studies, influenced by the CAP and the margin between input-output prices. Our study shows that the presence of other economic activities in the territory can either provide opportunities for diversifying farming revenues and counteract farming decline or bring challenges for silvopastoral systems such as increased competition for labor and land, depending on the characteristics of these activities and the contextual features. Agricultural abandonment was involved in most of the dominant feedback loops in both cases, with a higher influence in Guara where this phenomenon is already more prevalent. Conversely, in Lluçanès the capacity of farmers to access land was a more prominent factor defining the system behavior. Exogenous environmental socioeconomic and political factors also play a significant role in driving forest grazing. Although the sensitivity analysis revealed that the CAP and climate change were the major drivers reducing forest grazing in both case studies, advancements in technology can act as a catalyzer for increased forest grazing.

Despite the acknowledged role of forest grazing in reducing wildfire hazard and providing other ecosystem services, existing policies are not contributing to the spread of forest grazing. Transformative change in silvopastoral systems could be triggered by a broad range of targeted interventions in key factors. However, further investigation is required to quantify the potential impacts of these specific interventions in the dynamics of the systems through FCM-based scenario analysis. Finally, our work identifies commonalities but also differing regional factors in a shared trajectory of decline and shows that beyond the general decline of forest grazing, tailored policies are needed to address factors that can trigger desired transformational changes in silvopastoral systems.

Author Contributions:

Antonio Lecegui: Data curation; Formal analysis; Methodology; Writing-original draft review & editing.
Ana María Olaizola: Conceptualization; Formal analysis; Methodology; Supervision; Writing- review & editing.
Kasper Kok: Supervision; Writing-review & editing.
Elsa Varela: Conceptualization; Data curation; Formal analysis; Methodology; Funding acquisition; Investigation; Project administration; Supervision; Writing-review & editing.

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Data Availability:

Data/code available on request because of privacy/ethical restrictions.

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Appendix 1.

1. Preliminary list of factors

Table 1A. List of preliminary factors influencing forest grazing discussed with experts.

Social and cultural	Technical and technological	Economic and market	Environmental	Political or Institutional
Rural depopulation	Professionalization and labour availability	Difference between the inputs and outputs prices	Climate change	Common Agricultural Policy (CAP)
Agricultural abandonment	Availability of crops and foragein the farms	Beef and lamb meat demand	Wild fauna	Environmental policies
Sector attractiveness and generational turnover	Difficulties of forest grazing	Wood and bioenergy demand	Wildfire hazard and others biotic limitations	
Social perception of environmental issues	Infrastructure for forest grazing:	Tourism and recreational activities	Forest expansion	
Organization of the sector	Forest management	Access to farmland for buying or renting		
	Presence of local timber industries			
	Presence of local facilities for the transformation of livestock products			
	Technology and innovation			
	Presence of other types of livestock systems			
	Forest Management Planning			
	Herd/flock size			
	Intensification of the reproduction system			

2. FCMs post-processing

Before translating the causal maps generated during the workshops into adjacency matrices to create the FCM model (Kok 2009), the initial maps built by stakeholders often need to be adjusted and calibrated to enable computation and improve meaningful interpretations which may require factors and relationships to be added, removed, or modified (Jetter and Kok 2014).

2.1. Adjustment

The adjustment focused on listing and describing all the relationships identified in each workshop in order to check for missing relationships, redundancy or overly detailed relationships and those with very different time lags (Jetter and Kok 2014, Diniz et al.

2015). First, missing relationships not included in the FCM but mentioned during discussions were added from the audio recording of the workshop. The relationships representing the same process were eliminated to simplify redundancies. For instance, stakeholders in Lluçanès identified raid horse breeding (C13) to cause agricultural abandonment at the time that raid horse breeding (C13) was signalled to reduce access to land (C15) which in turn produces agricultural abandonment (C1) (**Fig. 1A**). Thus, direct relationship from C13 to C1 was removed to avoid the repetition. On the other hand, the connections with very different timeframes were also removed to synchronize time-lags in the map. We only found one connection with an outdated timeframe between environmental knowledge and climate change ("the environmental sensitivity of the population can exert pressure and implement actions to reduce climate change").

After the adjustment, all the information was synthesized, digitalised, and sent to participants for validation and completing the assignment of weights in the relationships. We listed the connections identified (except those identified collectively during the workshop) and asked stakeholders to select the 6 that they considered most influential within each sign. The connections identified in the workshop were considered the strongest relationships and assigned numerical values of 0.8 while the remaining were given a value of either 0.5 or 0.2 depending on the number of ratings obtained (33% of relationships in each category).

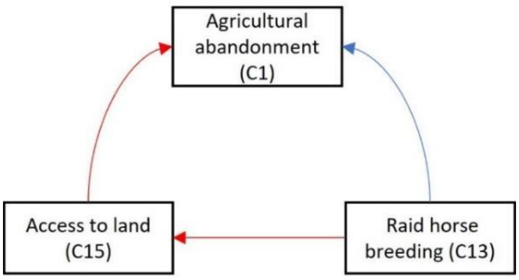

Fig. 1A. Example of definitional or overly detailed causal links.

2.2. Calibration

In the case of Guara, the model stabilized after 17 iterations (**Fig *2*A**). The dynamic output reflected a situation where the attractiveness of the sector (C2) had the highest values, followed by forest grazing (CO) while agricultural abandonment (C1) obtained the lowest values. The unexpected low values obtained by agricultural abandonment in Guara contrast with the current trend of farm abandonment observed in the livestock census which leads us to continue calibrating the map to obtain a more plausible behaviour of the model. Dynamic output in Lluçanès showed a situation with a high sector attractiveness (C2) and very low access to land (C15) (**Fig 3A**).

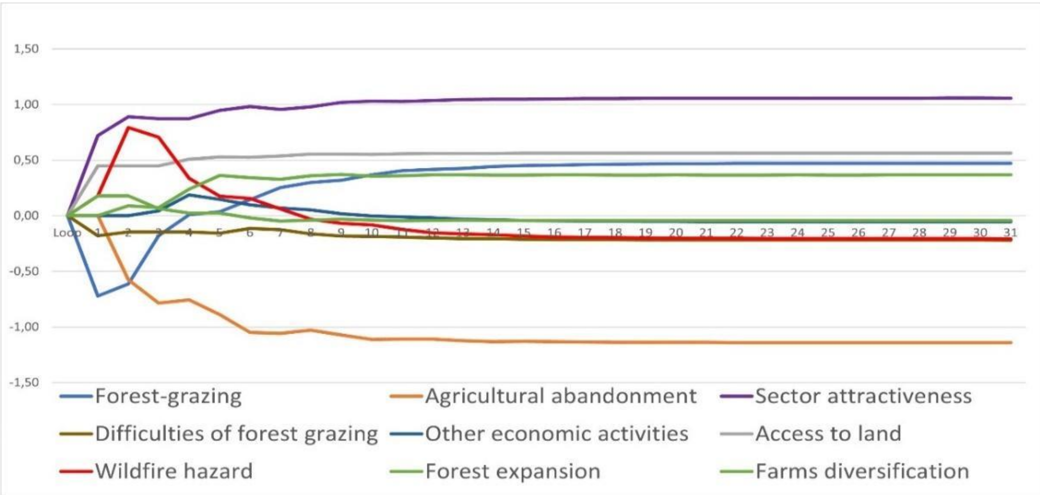

Fig 2A. Dynamic output from the initial maps built by stakeholders in Guara (raw).

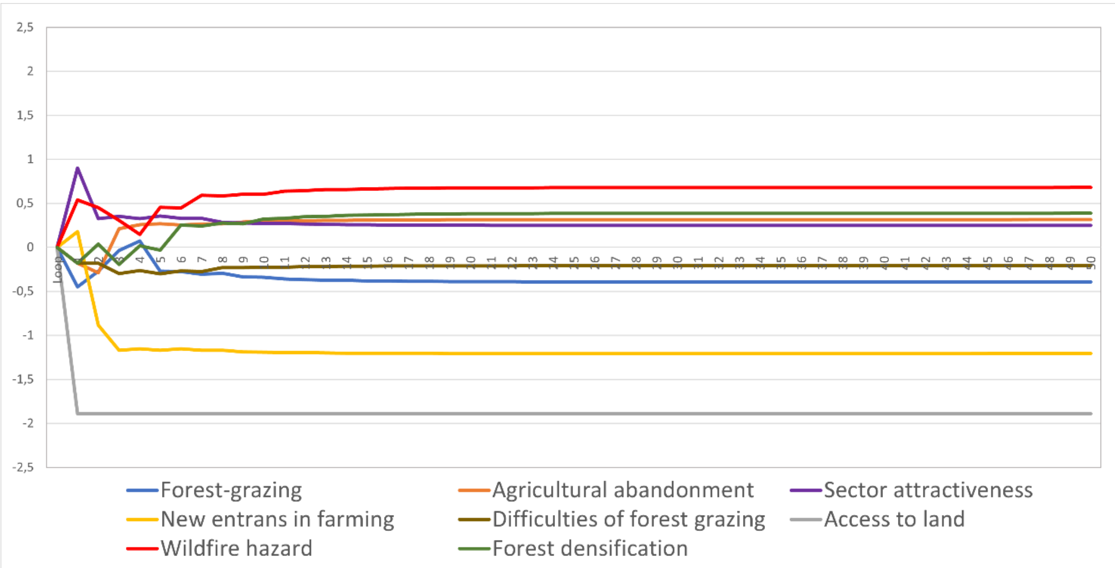

Fig 3A. Dynamic output from the initial maps built by stakeholders in Lluçanès (raw).

1.1. Re-calibration (Model modification)

In order to improve the capacity of the model to describe both system behavior and stakeholders' knowledge of forest grazing, and as part of the co-production process, some relationships were modified using the references collected during the workshops on participants' expectations for the system dynamic behavior. In the case of Guara the main reason for the re-calibration was that the initial dynamic results did not fit the knowledge of stakeholders on the system which was mainly due to the low values obtained for agricultural abandonment. As shown in **Table 2A** we weakened two connections, strengthened one and included two additional connections. In Lluçanès, we cancelled the driver role of the structure of the sector (**Table 3A**).

Table 2A. Changes in the relationships made after the workshop to calibrate the FCM in Guara.

Factors		**Weight**		
Initial	**Final**	**Raw**	**Calibrated**	**Interpretation**
Sector attractiveness (C2)	Agricultural abandonment (C1)	-0,5	-0,2	Despite the importance of the attractiveness of the sector to reduce abandonment, it is not the case in Guara
Other economic activities (C12)	Agricultural abandonment (C1)	-	0,8	Other economic activities (tourism) can either complement farm income (diversification) or compete with farm labor contributing to abandonment[†]
Climate change (C16)	Gap in prices (C11)	-0,2	-0,5	
Farms diversification (C5)	Agricultural abandonment (C1)	-0,8	-0,2	Other economic activities (tourism) can either complement farm income (diversification) or compete with farm labor contributing to abandonment[†]
Wildfire hazard (C18)	Agricultural abandonment (C1)	-	0,5	

[†] There is an ongoing debate on the role of other economic activities (i.e., tourism) on farm continuity. Although some authors argue that tourism is the main cause of farm abandonment (Bernués et al., 2011; Salukvadze and Backhaus, 2020), others claim that tourism play a synergic role with farm and enables to diversify sources of income, contributing to their continuity (Olaizola et al. 2015, Muñoz-Ulecia et al., 2021). We reflected that situation in the Revised FCM of Guara by adding the connection between Other economic activities (C11) and Agricultural abandonment (C1).

Table 3A. Changes in the relationships made after the workshop to calibrate the FCM in Guara.

Factors		**Weight**		
Initial	**Final**	**OLD**	**NEW**	**Interpretación**

Agricultural abandonment (C1)	Structure of the sector (C6)	-	-0,2	To eliminate the driver role from the structure of the sector
Wildfire hazard (C18)	Agricultural abandonment (C1)	-	0,2	Similar feedback loop than in Guara

2. Analysis of FCM

2.1. Structural analysis

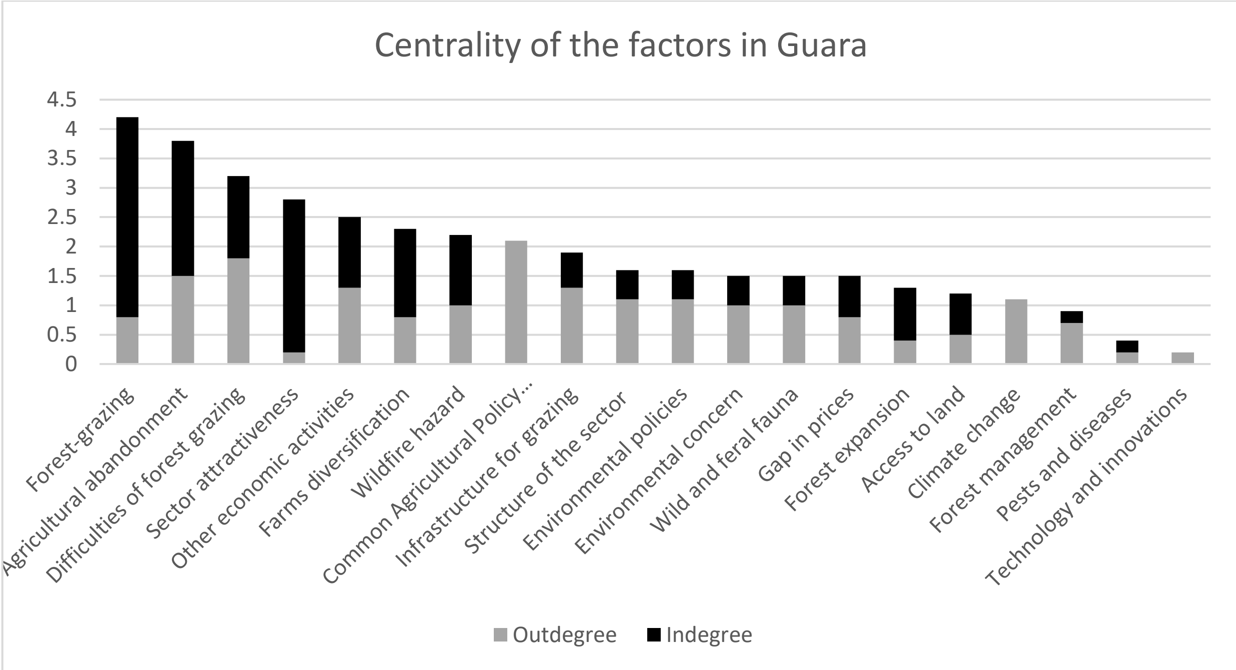

Fig 4A. Characteristics of the factors in the FCM in Guara.

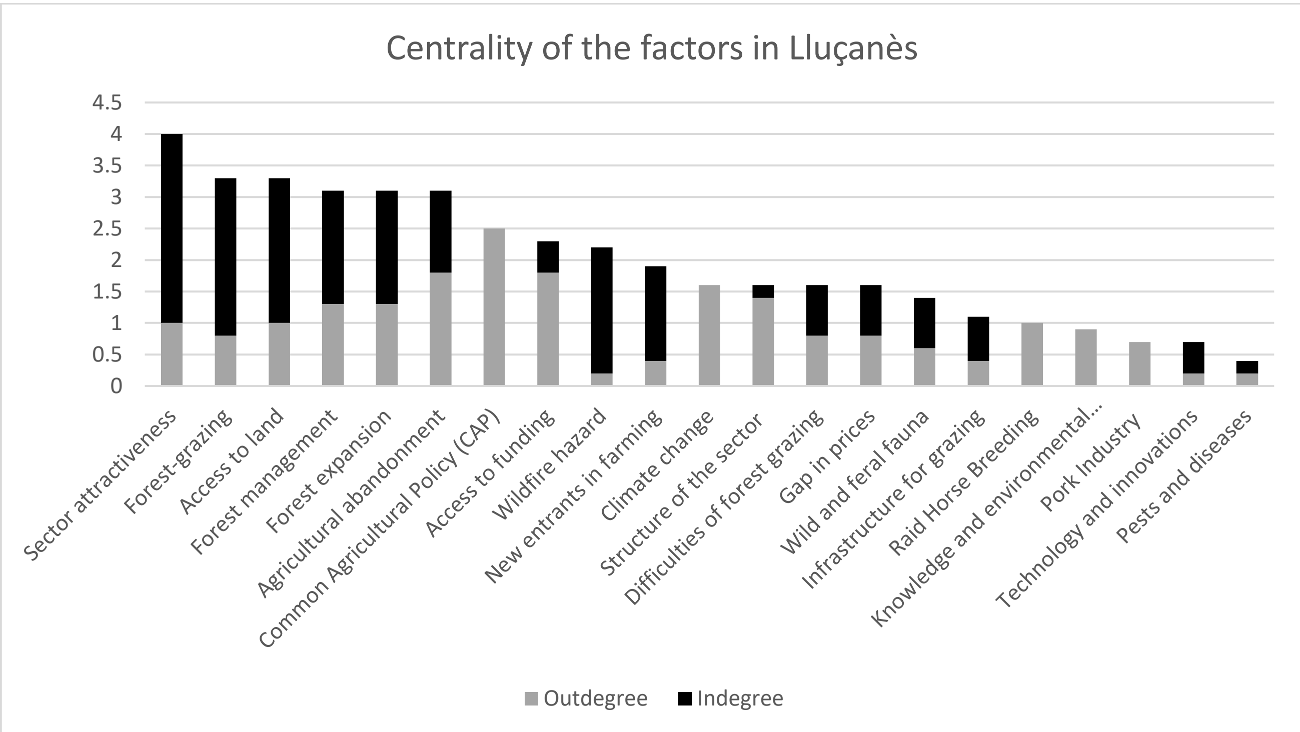

Fig 5A. Characteristics of the factors in the FCM in Lluçanès.

2.2. Loop Dominance

Table 4A. Feedbacks loops driving forest grazing in Guara. Variables involved, loop score and dominance (%).

Loop	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Pressure/Score	Dominance (%)
1	C1	C0	C18									0.320	44,42
2	C1	C0	C18	C4	C12							0.128	17,77
3	C1	C0	C18	C4	C12	C5						-0.016	-2,22
4	C1	C0	C18	C4	C22	C8	C7	C2				0.002	0,22
5	C1	C0	C18	C4	C22	C8	C7	C5				0.002	0,22
6	C1	C0	C18	C4	C22	C10	C8	C7	C2			0.000	-0,04
7	C1	C0	C18	C4	C22	C10	C8	C7	C5			0.000	-0,04
8	C1	C0	C18	C4	C22	C12						-0.026	-3,55
9	C1	C0	C18	C4	C22	C12	C5					0.003	0,44
10	C1	C0	C18	C4	C22	C17	C7	C2				0.004	0,56
11	C1	C0	C18	C4	C22	C17	C7	C5				0.004	0,56
12	C1	C0	C18	C4	C22	C17	C12					0.032	4,44
13	C1	C0	C18	C4	C22	C17	C12	C5				-0.004	-0,56
14	C1	C6	C8	C0	C18							0.032	4,44
15	C1	C6	C8	C0	C18	C4	C12					0.013	1,78
16	C1	C6	C8	C0	C18	C4	C12	C5				-0.002	-0,22
17	C1	C6	C8	C0	C18	C4	C22	C12				-0.003	-0,36
18	C1	C6	C8	C0	C18	C4	C22	C12	C5			0.000	0,04
19	C1	C6	C8	C0	C18	C4	C22	C17	C7	C2		0.000	0,06
20	C1	C6	C8	C0	C18	C4	C22	C17	C7	C5		0.000	0,06
21	C1	C6	C8	C0	C18	C4	C22	C17	C12			0.003	0,44
22	C1	C6	C8	C0	C18	C4	C22	C17	C12	C5		0.000	-0,06
23	C1	C6	C8	C7	C2							0.005	0,69
24	C1	C6	C8	C7	C0	C18						0.016	2,22
25	C1	C6	C8	C7	C0	C18	C4	C12				0.006	0,89
26	C1	C6	C8	C7	C0	C18	C4	C12	C5			-0.001	-0,11
27	C1	C6	C8	C7	C0	C18	C4	C22	C12			-0.001	-0,18
28	C1	C6	C8	C7	C0	C18	C4	C22	C12	C5		0.000	0,02

Loop	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Pressure/Score	Dominance (%)
29	C1	C6	C8	C7	C0	C18	C4	C22	C17	C12		0.002	0,22
30	C1	C6	C8	C7	C0	C18	C4	C22	C17	C12	C5	0.000	-0,03
31	C1	C6	C8	C7	C5							0.005	0,69
32	C1	C6	C11	C2								0.016	2,22
33	C1	C6	C15	C2								0.010	1,39
34	C1	C6	C5									0.050	6,94
35	C1	C20	C0	C18								0.016	2,22
36	C1	C20	C0	C18	C4	C12						0.006	0,89
37	C1	C20	C0	C18	C4	C12	C5					-0.001	-0,11
38	C1	C20	C0	C18	C4	C22	C8	C7	C2			0.000	0,01
39	C1	C20	C0	C18	C4	C22	C8	C7	C5			0.000	0,01
40	C1	C20	C0	C18	C4	C22	C10	C8	C7	C2		0.000	0,00
41	C1	C20	C0	C18	C4	C22	C10	C8	C7	C5		0.000	0,00
42	C1	C20	C0	C18	C4	C22	C12					-0.001	-0,18
43	C1	C20	C0	C18	C4	C22	C12	C5				0.000	0,02
44	C1	C20	C0	C18	C4	C22	C17	C6	C2			0.000	0,03
45	C1	C20	C0	C18	C4	C22	C17	C6	C5			0.000	0,03
46	C1	C20	C0	C18	C4	C22	C17	C12				0.002	0,22
47	C1	C20	C0	C18	C4	C22	C17	C12	C5			0.000	-0,03
48	C1	C20	C18									0.020	2,78
49	C1	C20	C18	C4	C12							0.008	1,11
50	C1	C20	C18	C4	C12	C5						-0.001	-0,14
51	C1	C20	C18	C4	C22	C8	C7	C2				0.000	0,01
52	C1	C20	C18	C4	C22	C8	C7	C5				0.000	0,01
53	C1	C20	C18	C4	C22	C10	C8	C7	C2			0.000	0,00
54	C1	C20	C18	C4	C22	C10	C8	C7	C5			0.000	0,00
55	C1	C20	C18	C4	C22	C12						-0.002	-0,22
56	C1	C20	C18	C4	C22	C12	C5					0.000	0,03
57	C1	C20	C18	C4	C22	C17	C7	C2				0.000	0,03
58	C1	C20	C18	C4	C22	C17	C7	C5				0.000	0,03
59	C1	C20	C18	C4	C22	C17	C12					0.002	0,28
60	C1	C20	C18	C4	C22	C17	C12	C5				0.000	-0,03

Loop	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Pressure/Score	Dominance (%)
61	C4	C22	C8	C0	C18							0.032	4,44
62	C4	C22	C8	C7	C0	C18						0.016	2,22
63	C4	C22	C10	C8	C0	C18						-0.006	-0,89
64	C4	C22	C10	C8	C7	C0	C18					-0.003	-0,44
65	C4	C22	C10	C20	C0	C18						-0.004	-0,56
66	C4	C22	C10	C20	C18							-0.005	-0,69
67	C4	C22	C17	C7	C0	C18						0.040	5,55
												0.720	

Table 5A. Feedback loops driving forest grazing in Lluçanès. Variables involved, loop score and dominance (%)

Loop	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Pressure /Score	Dominance (%)
1	C1	C6	C2								0.080	13.23
2	C1	C6	C2	C3							0.016	2.65
3	C1	C6	C2	C3	C0	C20	C18				0.001	0.21
4	C1	C6	C8	C0	C20	C17	C2				0.001	0.08
5	C1	C6	C8	C0	C20	C17	C2	C3			0.000	0.02
6	C1	C6	C8	C0	C20	C17	C19	C2			0.000	0.02
7	C1	C6	C8	C0	C20	C17	C19	C2	C3		0.000	0.00
8	C1	C6	C8	C0	C20	C18					0.001	0.11
9	C1	C6	C8	C7	C0	C20	C17	C2			0.000	0.07
10	C1	C6	C8	C7	C0	C20	C17	C2	C3		0.000	0.01
11	C1	C6	C8	C7	C0	C20	C17	C19	C2		0.000	0.01
12	C1	C6	C8	C7	C0	C20	C17	C19	C2	C3	0.000	0.00
13	C1	C6	C8	C7	C0	C20	C18				0.001	0.08
14	C1	C6	C10	C0	C20	C17	C2				0.002	0.34
15	C1	C6	C10	C0	C20	C17	C2	C3			0.000	0.07
16	C1	C6	C10	C0	C20	C17	C19	C2			0.000	0.07
17	C1	C6	C10	C0	C20	C17	C19	C2	C3		0.000	0.01
18	C1	C6	C10	C0	C20	C18					0.003	0.42
19	C1	C6	C10	C18							0.004	0.66
20	C1	C6	C15								0.008	1.32

Loop	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Pressure /Score	Dominance (%)
21	C1	C6	C15	C3							0.006	1.06
22	C1	C6	C15	C3	C0	C20	C17	C2			0.000	0.07
23	C1	C6	C15	C3	C0	C20	C17	C19	C2		0.000	0.01
24	C1	C6	C15	C3	C0	C20	C18				0.001	0.08
25	C1	C10	C0	C20	C17	C2					0.041	6.77
26	C1	C10	C0	C20	C17	C2	C3				0.008	1.35
27	C1	C10	C0	C20	C17	C19	C2				0.008	1.35
28	C1	C10	C0	C20	C17	C19	C2	C3			0.002	0.27
29	C1	C10	C0	C20	C18						0.051	8.47
30	C1	C10	C18								0.080	13.23
31	C1	C20	C17	C2							0.064	10.58
32	C1	C20	C17	C2	C3						0.013	2.12
33	C1	C20	C17	C19	C2						0.013	2.12
34	C1	C20	C17	C19	C2	C3					0.003	0.42
35	C1	C20	C18								0.080	13.23
36	C2	C3	C0	C20	C17						0.013	2.12
37	C2	C3	C0	C20	C17	C19					0.003	0.42
38	C0	C20	C17	C7							0.102	16.93
											0.605	

2.3. Sensitivity analysis

Table 6A. Sensitivity analysis of drivers on system´s factors in Guara.

		Driver 1: Technology and innovations		Driver 2: Climate change		Driver 3: CAP	
		Coeff.	**R^2**	**Coeff.**	**R^2**	**Coeff.**	**R^2**
Forest-grazing	FF	0.75	0.11	-1.18	0.27	-1.79	0.66
Agricultural abandonment	C1	-0.52	0.13	1.02	0.50	0.89	0.41
Sector attractiveness	C2	0.18	0.03	-0.63	0.33	0.85	0.64
Environmental concern	C4	-0.31	0.10	0.61	0.37	0.73	0.57
Farms diversification	C5	0.19	0.42	-0.20	0.46	-0.12	0.17
Structure of the sector	C6	0.26	0.13	-0.51	0.50	0.17	0.22
Difficulties of forest grazing	C7	-0.28	0.56	0.20	0.28	0.17	0.22

Infrastructure for grazing	C8	0.08	0.12	-0.15	0.46	-0.15	0.46
Technology and innovations	C9	1.00	1.00	-0.04	0.00	-0.04	0.00
Forest management	C10	-0.03	0.10	0.06	0.37	0.07	0.57
Gap in prices	C11	0.07	0.01	-0.60	0.97	-0.09	0.02
Other economic activities	C12	-0.16	0.10	0.32	0.37	0.38	0.57
Access to land	C15	0.03	0.01	-0.10	0.05	0.41	0.94
Climate change	C16	-0.04	0.00	1.00	1.00	0.00	0.00
Wild and feral fauna	C17	-0.08	0.10	0.15	0.37	0.18	0.57
Wildfire hazard	C18	-0.63	0.10	1.21	0.37	1.46	0.57
Pests and diseases	C19	-0.01	0.00	0.20	1.00	0.00	0.00
Forest expansion	C20	-0.10	0.06	0.37	0.84	0.14	0.13
Common Agricultural Policy (CAP)	C21	-0.04	0.00	0.00	0.00	1.00	1.00
Environmental policies	C22	-0.16	0.10	0.30	0.37	0.36	0.57

Table 7A. Sensitivity analysis of drivers on system´s factors in Lluçanès.

		Driver 1 Knowledge and environmental education		Driver 2 Raid Horse Breeding		Driver 3 Pork Industry		Driver 4 Climate change		Driver 5: Common Agricultural Policy	
		Coeff.	**R²**	**Coeff.**	**R²**	**Coeff.**	**R²**	**Coeff.**	**R²**	**Coeff.**	**R²**
Forest-grazing	C0	0.73	0.38	-0.57	0.25	-0.09	0.01	-0.66	0.32	-0.10	0.01
Agricultural abandonment	C1	-0.60	0.30	0.52	0.23	-0.09	0.00	0.73	0.43	-0.05	0.00
Sector attractiveness	C2	0.78	0.42	-0.20	0.03	-0.05	0.00	-0.73	0.35	0.50	0.17
New entrants in farming	C3	0.09	0.01	-0.68	0.60	-0.38	0.18	-0.12	0.02	-0.39	0.19
Knowledge and environmental education	C4	1.00	1.00	0.03	0.00	-0.01	0.00	0.01	0.00	0.00	0.00
Structure of the sector	C6	0.12	0.30	-0.10	0.23	0.00	0.00	-0.15	0.43	0.01	0.00
Difficulties of forest grazing	C7	-0.38	0.71	0.10	0.05	0.02	0.00	0.18	0.16	-0.09	0.04
Infrastructure for grazing	C8	0.02	0.01	-0.02	0.00	-0.01	0.00	-0.03	0.02	0.25	0.97
Technology and innovations	C9	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.25	1.00
Forest management	C10	0.51	0.25	-0.43	0.18	-0.02	0.00	-0.61	0.36	0.44	0.18
Gap in prices	C11	-0.04	0.00	-0.02	0.00	-0.02	0.00	-0.80	1.00	0.01	0.00

Raid Horse Breeding	C13	0.01	0.00	1.00	1.00	-0.01	0.00	0.02	0.00	0.02	0.00
Pork Industry	C14	0.01	0.00	-0.01	0.00	1.00	1.00	0.03	0.00	-0.03	0.00
Access to land	C15	0.01	0.00	-0.83	0.46	-0.46	0.14	-0.06	0.00	-0.80	0.40
Climate change	C16	0.05	0.00	0.02	0.00	0.03	0.00	1.00	1.00	-0.01	0.00
Wild and feral fauna	C17	-0.85	0.39	0.54	0.16	0.07	0.00	0.88	0.41	0.03	0.00
Wildfire hazard	C18	-0.95	0.22	0.56	0.08	0.08	0.00	1.66	0.66	-0.21	0.01
Pests and diseases	C19	-0.17	0.39	0.11	0.16	0.01	0.00	0.18	0.41	0.00	0.00
Forest expansion	C20	-1.07	0.39	0.67	0.16	0.09	0.00	1.11	0.41	0.03	0.00
Common Agricultural Policy	C21	0.00	0.00	0.02	0.00	-0.03	0.00	-0.01	0.00	1.00	1.00
Access to funding	C23	0.00	0.00	0.01	0.00	-0.02	0.00	0.00	0.00	0.50	1.00

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