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Socioeconomic and land-use factors shape sustainable management in the Catalan Pyrenees

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Mountain social-ecological systems are facing profound land-use, climatic, and socioeconomic changes, and sustainable management requires understanding how different system elements interact and align with local stakeholders' preferences. Here, we used socioeconomic and environmental data to develop a multi-stage quantitative framework to identify processes involved in trade-offs and convergences between scenarios satisfying different stakeholders in the Catalan Pyrenees. We explored system trajectories leading to potential future scenarios with outcomes favourable to various stakeholders using a dynamical network model. Further, a classification tree allowed us to identify key drivers of desired outcomes. Our results show that socioeconomic and land-use factors are crucial for the determination of system trajectories that meet the needs of different stakeholders. Strategies such as limiting forest expansion and balancing tourism and agriculture can align with stakeholder priorities. Our approach can inform management strategies that meet diverse development goals while accounting for the complexity of the social-ecological system dynamics.

Mountains have long been managed and shaped by human societies. They constitute an emblematic example of social-ecological systems (SESs)[1], embodying the paradigmatic shift from viewing nature and society as separate entities to recognising their interconnectedness as parts of the same system[2,3]. Interactions among SES elements create feedbacks that influence the system's resilience, adaptive capacity and transformability in sometimes unpredictable ways[4,5]. However, due to the complex nature of SESs, their outcomes cannot be fully understood by considering them just as the sum of their parts[6,7]. Accounting for the direct and indirect relationships among SES elements is thus necessary to understand not only their behaviour and persistence, but also their responses to different drivers of change. Mountain SESs' biophysical and cultural complexity, cross-scale ecosystem services, physical isolation, and marginalisation from decision-making centres make them particularly vulnerable to climate change[1]. Their sustainability is weakened by changes occurring at several scales, from top-down markets and governance strategies or climate change, to sociocultural, demographic and political transformations[8–12]. Overcoming these challenges depends on our ability to understand mountain SESs' dynamics and requires developing mitigation strategies involving stakeholders and decision-makers[1].

Mountain SESs are often subjected to unsuitable top-down management policies imposed by outsiders[1], potentially giving rise to conflicts[13] or maladaptation[14] due to the diverse priorities among co-existing inhabitants. A key challenge in such contexts is people's subjective, context-dependent and incomplete representations of reality[15–17], or mental models, which are shaped by culture, education, values and experiences[18–20], and in turn determine people's behaviour and decisions[21,22]. This makes decision-making a complex process as stakeholders may have diverging and competing preferences regarding the management of their environment, e.g. ref. 23.

The Pyrenean mountains, in the northern Iberian Peninsula, exemplify the socioeconomic challenges faced by most European and potentially worldwide mountain regions, characterized by high depopulation during the second half of the 20th century. They have transitioned from an economy based on agriculture and farming to one based on services[24,25]. In this context, divergent views have emerged among local inhabitants regarding the region's future development[26], raising potential challenges when defining adaptation measures aimed at mitigating social and environmental changes[14].

Clarifying trade-offs and areas of alignment between stakeholders' objectives and incorporating local perspectives in decision-making is critical for inclusive regional policy planning[27]. By integrating social, ecological and economic processes and weighing competing stakeholders' interests, SES modelling frameworks can help address complex social-ecological challenges. Such efforts can foster opportunities for compromise[27,28], and may

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result in decisions that better fit local needs and priorities in contexts such as landscape planning[29], reconciling development and biodiversity conservation[30], or designing resilience actions to face climate change[31].

Models with high representational detail have the potential to closely match observable mechanisms of real-world systems and support decision-making, but they are often difficult to parametrize and to interpret, and may be challenging to use for broad scenario exploration[32]. Conversely, more theoretical or conceptual models are simpler and focus on generic processes rather than case-specific details. SES models with an intermediate level of abstraction and grounded on empirical data can represent selected aspects of the SES relevant to the model's purpose, and can be used as "virtual laboratories" to test hypotheses or improve understanding of the system's behaviour[32,33]. They may also serve as the baseline for developing higher-fidelity models[32] and for identifying effective intervention points for governance[33].

In this paper, we aim to elucidate trade-offs and synergies between competing stakeholder priorities and potential intervention points in a mountain SES that could facilitate the development of sustainable management strategies capable of aligning the diverse local objectives across stakeholders. To achieve this, we propose a multi-stage modelling framework (Fig. 1) drawing from (1) a previously developed quantitative static network model formalizing interactions among 31 elements of a Pyrenean mountain SES[34], including water resources, biodiversity, and socio-economic, land-use, climatic and other environmental elements (Fig. 2a, b); and (2) local perspectives and priorities regarding rural development in the Pyrenees, as described by López-i-Gelats et al.[26] (Fig. 2c). Using the SES representation from Zango-Palau et al.[34] as a baseline model defining the relationships between SES components, we developed a dynamical model to simulate the dynamics of the system components through time. This dynamical model allows us to define and estimate from empirical data key parameters such as intrinsic growth rates (r), interaction coefficients (a_{ij}) and self-regulation coefficients (a_{ii}) (see Fig. 1 and "Methods" for parameter definition) that can be used to investigate the components' contributions to system dynamics under different scenarios. We fixed interaction coefficients as these have been established in a previous study[34] and explored the system's possible trajectories under a wide range of varying combinations of r values to simulate a multitude of plausible development scenarios. We used evidence on local discourses and priorities[26] to relate model scenarios to four mental frameworks: conservationist, entrepreneurial, agriculturalist and endogenous development. These differ notably in their values and priorities regarding the economy, nature conservation, tourism development, and traditional landscapes. We refer to the shared, group-level perspectives as "mental frameworks", emphasizing their typological nature rather than individual mental models. We translated such priorities into satisfaction criteria applied to selected SES indicators in the model, which enabled us to assess which simulated development trajectories satisfy one or more of these mental frameworks. Finally, we used a classification tree model to identify the key drivers of the social-ecological system shaping its trajectory towards different types of satisfaction scenarios: "agriculturalist-only", "conservationist-only", "entrepreneur-only" and "endogenous development only" (i.e., scenarios where only one of the stakeholders' mental frameworks is considered as satisfied, respectively), and "all inclusive" (i.e., scenarios where all four are satisfied) (Fig. 2c). We expected that scenarios where all mental frameworks are satisfied would emerge under conditions that balance diverging priorities (e.g. economic diversification vs. focus on tourism or agriculture) and/or fulfil shared priorities (e.g., regarding landscape composition).

Our study shows that socioeconomic and land-use factors are the main factors determining the system's trajectory towards diverging scenarios aligned with different stakeholders' mental frameworks. In particular, diversifying the economy and addressing the issue of agricultural land abandonment and recolonisation by forests appear related to the scenarios showing highest satisfaction across stakeholders. This study contributes to a broader understanding of how analysing SES dynamics can provide insights to support management strategies that integrate diverse local priorities and promote sustainable development at regional scales.

Results

Our methodological framework allowed to explore how different system trajectories aligned with the four stakeholders' mental frameworks defined above. To this end, we simulated the dynamical behaviour of the SES and assessed stakeholder satisfaction for each simulation. A classification tree enabled us to identify the key drivers of stakeholder satisfaction and the thresholds beyond which certain combinations of intrinsic growth rates (r) values are linked with different satisfaction scenarios. We focused on seven groups of simulation outputs representing a substantial and representative proportion of the total (see "Methods"). The key factors distinguishing these seven groups were the intrinsic growth rates of *services GDP* (gross domestic product), *salary in agriculture*, *max summer temperature*, *forests*, *summer seasonal population*, *tourism establishments*, *meadows, bushes, and fields*, and *summer snow* (Fig. 3). We assessed stakeholder satisfaction and the relative change from the original r value (r_0) for the differentiating factors of each stakeholder satisfaction scenario type (see "Methods").

Landscape composition and economic factors drive differences between stakeholder satisfaction scenarios

Simulation outputs belonging to the "agriculturalist-only" scenario type differed from others in their r values of *services GDP* (remaining close to the original value, r_0), *salary in agriculture* (decreasing on average by 28%), *forests* (mean growth of 37%), *summer seasonal population* (declining by an average of 47%), and *tourism establishments* (overall increasing by 29%, though remaining below 0.225) (Figs. 3 and 4). These simulations met on average 53% of the agriculturalist's criteria. Land use criteria (see Table 1 and Supplementary Methods) were never met, and there was high variability in the fulfilment of the biodiversity criteria. *Second homes* failed to meet the agriculturalist's requirements in 75% of the simulations (Fig. 5a and Table 1).

The "conservationist-only" scenario type was associated with increasing r values for *services GDP* (+12%, with values ranging between -25% and 50%), *salary in agriculture* (+24%) and *forests* (+18%), and a mean decrease of 8% in the r of *meadows, bushes, and fields*, though remaining above a threshold value of 0.91 (Figs. 3 and 4). The conservationist's criteria were almost always met regarding urbanisation, forests and the abundance of birds and butterflies, but not those related to *meadows, bushes, and fields*, the balance between *agriculture* and *services GDP*, or *butterfly richness*. *Second homes* predominantly exceeded the preferred limit for the conservationist (Fig. 5a and Table 1). Simulations belonging to this scenario type fulfilled on average 56% of the conservationist's satisfaction criteria.

The "entrepreneur-only" scenario type was associated with a growth in the r of *services GDP* (+12%), the r of *salary in agriculture* (+22%), *forests* (+36%), a decrease of 28% in *the r* of *meadows, bushes, and fields* and a mean increase in that of *tourism establishments* by 36% (Figs. 3 and 4). Regarding the entrepreneur's criteria, *winter seasonal population*, a measure of ski tourism, only reached its desired number in half of the cases, and the two criteria related to land abandonment were never met. *Resident population* and the balance between *agriculture GDP* and *services GDP* reached their optimal values for this mental framework in all the cases (Fig. 5a). On average, 64% of the entrepreneur's criteria per simulation were met.

The "endogenous development only" scenario type was differentiated by the r values of *services GDP*, *maximum summer temperature* and *summer flow*, decreasing notably, with averages of −40%, −25% and −30% respectively (Figs. 3 and 4). Only half of this mental framework's criteria were met in these simulations: the requirements regarding *winter seasonal population*, *second homes* and *resident population* were fulfilled in all of them, but the economic and land use criteria were never met (Fig. 5a). Despite 99% of simulations belonging to the "endogenous development only" scenario being successfully classified into the same subset, these represented only 10% of the whole subset of simulations with the same combination of tree splitting conditions. Additionally, simulations in this scenario type only fulfilled 50% of the criteria of the endogenous

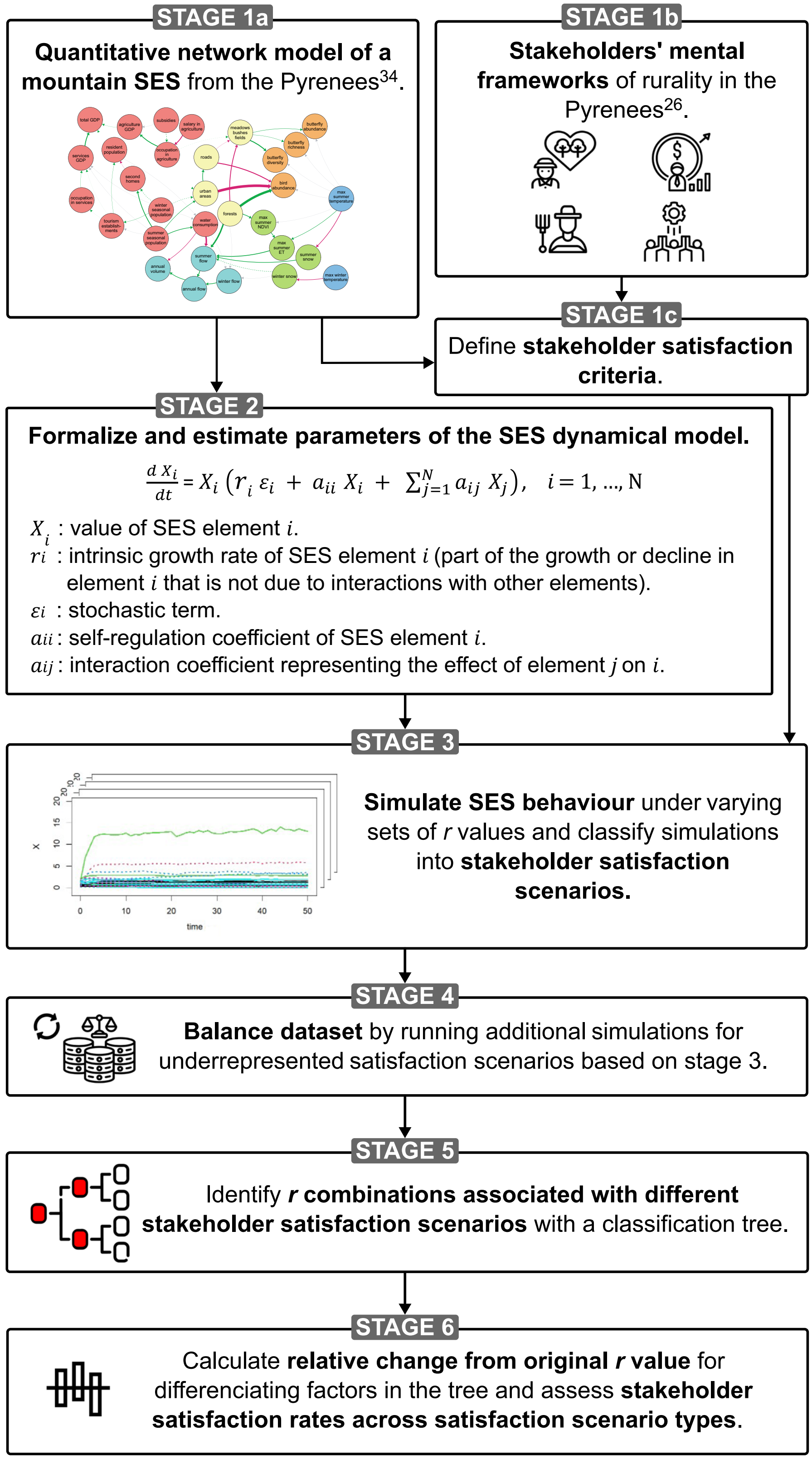

Fig. 1 | A multi-stage modelling and analysis framework integrating stakeholder perspectives to inform sustainable social-ecological systems (SESs) management. In stage 1 a network comprising socioeconomic and ecological elements of the SES is defined based on expert knowledge on their relationships (1a and Fig. 2b). In parallel, satisfaction criteria defining the mental frameworks of the stakeholders involved in the system and used to classify model outputs into satisfaction scenarios are defined (1c) based on previous knowledge of the system (1a) and evidence on stakeholders' values and priorities (1b and Fig. 2c). During stage 2, a quantitative mathematical representation of the system is defined based on the information gathered in stage 1a. Stage 3 involves running numerical simulations to explore the system's behaviour under a variety of combinations of intrinsic growth rates (r) values, and classifying plausible simulation outcomes into actor satisfaction scenarios based on the criteria defined in stage 1c. In stage 4, additional exploratory simulations are run to balance the simulation outputs dataset across actor satisfaction scenarios. Stage 5 consists in performing a classification tree analysis to classify simulation outputs into homogenous subsets of data within which most of the observations belong to the same stakeholder satisfaction scenarios. The classification tree algorithm partitions the data based on the r values used in the simulation runs, and therefore enables the identification of the key SES elements whose r values are involved in differentiating the different stakeholder satisfaction scenarios. Lastly, stage 6 aims at analysing raw simulation outputs based on the classification tree predictions. Simulation outputs are divided into subsets following the splitting conditions predicted by the tree (e.g., Fig. 3), making it possible to quantify the relative change from the original r value for the key SES elements in the most relevant subsets for each stakeholder satisfaction scenario (e.g., Fig. 4). This also facilitates the evaluation of the percentage of simulations in every subset where each satisfaction criterium was met (e.g., Fig. 5). Arrows connecting the boxes indicate methodological flows between different stages. Full details on every stage and their relationships can be found in the "Methods" section. Icons for stages 1b, 4, 5 and 6 were designed by Freepik. The network figure illustrating stage 1a is adapted from Zango et al. (2024), licensed under CC BY 4.0.

development, and splitting variables (*max summer temperature* and *summer flow*) were not directly related to this stakeholders' priorities.

A balance between economic sectors and limiting forest growth can satisfy all stakeholders

From the three "all-inclusive" scenario types identified (A1, A2 and A3; Fig. 3), scenario type A2 grouped most of the "all-inclusive" simulations, though with only 56% of the criteria met on average across mental frameworks (54% for the agriculturalist, 56% for the conservationist, 55% for the entrepreneur and 60% for the endogenous development). Its differentiating factors and their respective relative growths from their r_0 were similar to the "agriculturalist-only" scenario type (Figs. 3 and 4), with the difference that the r of *tourism establishments* showed the highest relative growth across all satisfaction scenario types (+71%) (Fig. 4). Among the criteria relevant to all 4 stakeholders,

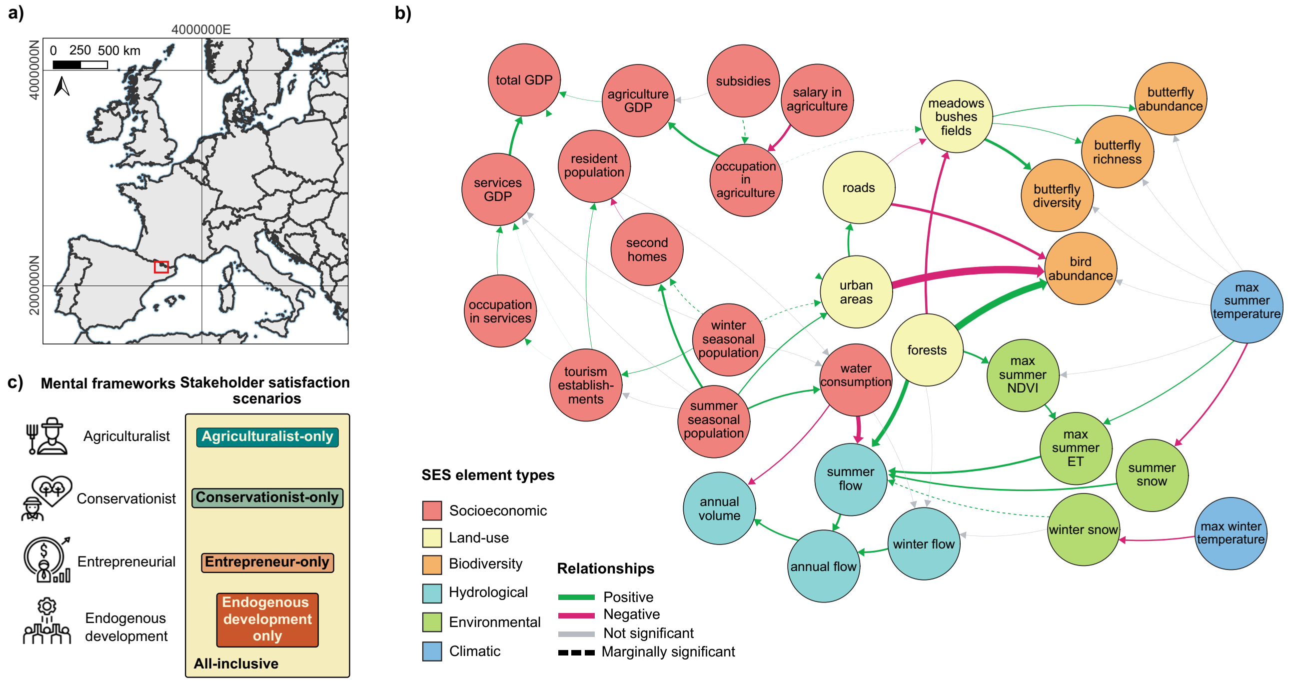

Fig. 2 | Location of the mountain social-ecological system (SES) of the Pyrenees, foundational network model of the SES and mental frameworks included in the study to define stakeholder satisfaction scenarios. **a** Location of the study area in Europe. The map uses the LAEA Europe projection (ETRS89-extended/LAEA Europe, EPSG:3035). **b** Integrated network of the mountain social-ecological system used as foundation for the study, adapted from Zango-Palau et al.[34] (licensed under CC BY 4.0.). Arrows indicate the relationships between 31 social-ecological variables, inferred through piecewise structural equation modelling. Dotted arrows indicate marginally significant relationships (p value < 0.1). For significant (p < 0.05) and marginally significant relationships, arrow width is proportional to standardized weight coefficients. Arrow colour indicates the type of relationship (green: positive, red: negative, grey: non-significant). The colour of the network nodes (circles) indicates the type of SES element (red: socioeconomic; yellow: land-use; orange: biodiversity; light blue: hydrological; green: environmental; purplish blue: climatic). **c** Mental frameworks identified in the Pyrenees by López-i-Gelats[26] used to classify simulation outputs into stakeholder satisfaction scenarios based on established quantitative criteria (see Fig. 1 and the "Methods" section for details). Stakeholder satisfaction scenarios are associated to the following colours: teal for the "agriculturalist-only", green for the "conservationist-only", orange for the "entrepreneur-only", red for the "endogenous development only" and yellow for the "all-inclusive". Icons representing the mental frameworks were designed by Freepik.

the proportion of *meadows, bushes, and fields* in the landscape was never satisfied for any stakeholder, whereas the proportion of *forests* was only agreeable for the conservationist (Fig. 5b and Table 1). The entrepreneur was the least favoured regarding the balance between *agriculture* and *services GDP*, and regarding *winter seasonal population*. Compared with their respective individual scenario types, the agriculturalist and the conservationist were satisfied regarding urbanisation in only half of the simulations, and biodiversity variables showed again disparate satisfaction rates for these two stakeholders (Fig. 5a, b).

Simulations belonging to A1 and A3 were differentiated by the r of *services GDP* (+11% in A1 and +7% in A3), *salary in agriculture* (+22% in A1 and −27% in A3) and *forests* (−23% in A1 and +0.6% in A3) (Fig. 3, Fig. 4). In A1, an average 68% of criteria were met per simulation (mean percentages of 75% for the agriculturalist, 74% for the conservationist, 64% for the entrepreneur and 59% for the endogenous development). In A3, an average of 63% of criteria were met per simulation (68% for the agriculturalist, 66% for the conservationist, 61% for the entrepreneur and 57% for the endogenous development). In both cases, satisfaction rates ranged up to 100% for the 4 stakeholders (Fig. 5b and Table 1).

Scenario type A1 differed substantially from A2 in several aspects (Fig. 5b). Landscape composition criteria were all fulfilled in at least 75% of the simulations across mental frameworks, except for the entrepreneur's urban areas requirement (met with a frequency of 27%). The balance between agriculture and services GDP favoured the entrepreneur in 95% of the simulations, contrasting with around 18% for the other stakeholders, while A2 showed opposite numbers. The entrepreneur's optimal *total GDP* values were also met much less frequently than in A2. Additionally, the optimal values for *second homes* (which concern all stakeholders except the entrepreneur) and for *resident population* (concerning the entrepreneur and the endogenous development) were only met in a minority of cases. All biodiversity criteria for the conservationist and agriculturalist were fulfilled in more than 75% of A1 simulations.

Finally, all-inclusive scenario type A3 showed intermediate frequencies of criteria fulfilment compared to A1 and A2 (Fig. 5b). Notably, the proportion of *forests* in the landscape met the optimal values for the conservationist in 99% of the simulations, as opposed to 43% for the remaining stakeholders. For all stakeholders, the criterion regarding the proportion of *meadows, bushes, and fields* was only met in 30% of the cases, and the one regarding balance between *agriculture* and *services GDP* was met in around 64% of simulations.

Discussion

Managing complex social-ecological systems, such as mountain regions, is a challenging task for which there are no universal measures to be implemented[35]. Scientific models help conceptualize future scenarios and, despite their constraints and limitations, they remain essential tools to structure complex data and explore potential outcomes[32,36–38]. Our multi-stage modelling approach identifies 8 key elements whose intrinsic growth rates (r) strongly influence shifts towards pathways leading to different stakeholder satisfaction scenarios: *services GDP*, *salary in agriculture*, *max summer temperature*, *forests*, *summer seasonal population*, *tourism establishments*, *meadows, bushes, and fields*, and *summer snow*. This allows us to uncover the divisive and consensual elements and processes in the system. Further, it serves as a tool to select specific social-ecological elements of the system that should be given priority in

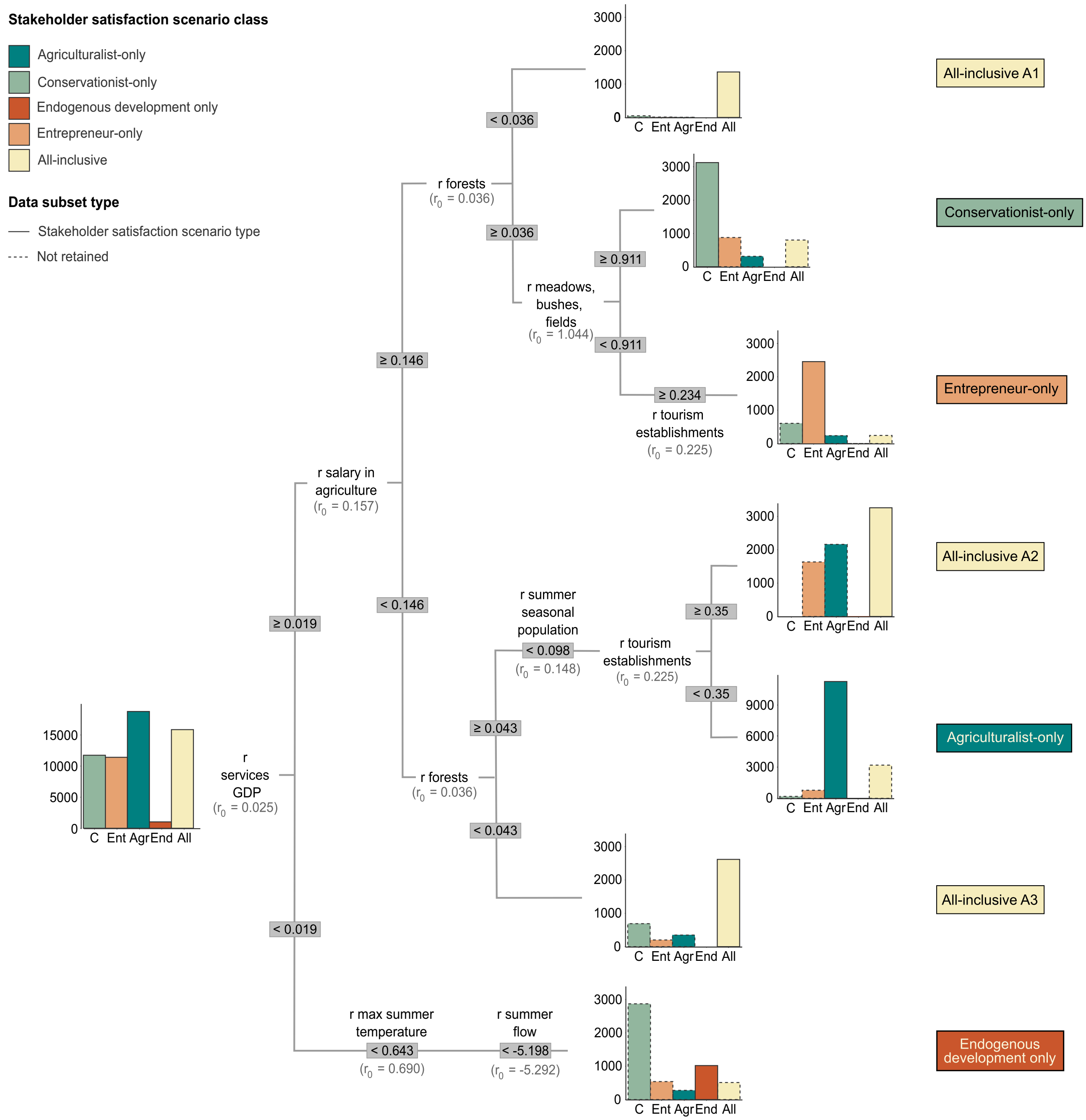

Fig. 3 | Classification tree partitions differentiating the seven most representative stakeholder satisfaction scenario types selected from the model's thirteen leaves (see Supplementary Fig. 5). Stakeholder satisfaction scenario types correspond to the true positives within the subsets obtained after filtering the raw data according to the classification tree predictions for the leaves. Only the cases where true positives constituted at least half of the simulation outputs in the subsets analogous to the leaves were selected in the case of the "conservationist-only" (green), "entrepreneur-only" (orange) and "agriculturalist-only" (teal) scenario types. The only existing subset for the "endogenous development only" (red) was retained, as well as all three subsets corresponding to the "all-inclusive" scenario, labelled A1, A2 and A3 (yellow). The shown tree structure and splitting conditions were replicated based on the classification tree, fitted with the *rpart* algorithm (cp = 0.00846), trained using repeated, stratified 10-fold cross-validation with hyperparameter tuning and evaluated on a stratified test set (see Supplementary Methods for details). The bar plot adjacent to the root of the tree shows the distribution of stakeholder satisfaction scenario classes in the raw simulation outputs, while the bar plots at the leaves show the distribution after filtering the data according to the tree splitting conditions. In the bar plots, the class corresponding to the selected subset has a full outline, while the other classes are shown with a dotted outline. r_0 corresponds to the original intrinsic growth rate.

management to drive it towards a state aligned with the local stakeholders' mental frameworks.

The key drivers for stakeholder satisfaction scenarios are mostly socioeconomic (4 of 8), and the others are related to land use (2 out of 8), to the water system (1 out of 8) and to climate (1 out of 8). In their synthesis of 71 mountain SES case studies, Gupta et al.[35] found that the four main drivers of change in mountain SESs worldwide were overexploitation, land use change, demographic change, and the regional economy. In the specific case of mountain SESs in developed countries, they identified an underuse of biological resources as an important driver of change. This underuse, closely linked to land abandonment, represents a key land-use driver of environmental change. Our results align with these findings, as the growth rates (r) of both *forests* and *meadows, bushes, and fields* appear as splitting variables, hinting towards the stakeholders' concerns on agricultural land

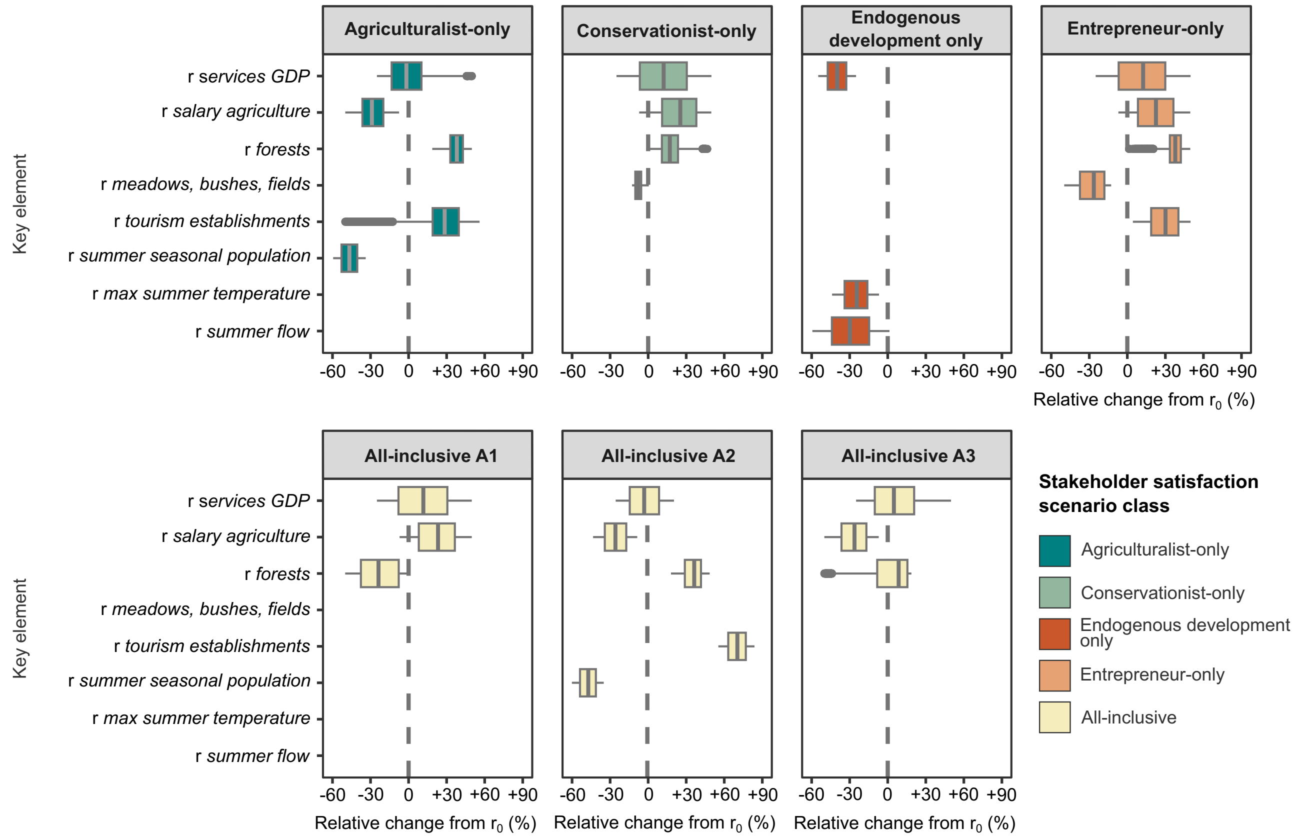

Fig. 4 | Relative change in the intrinsic growth rate of the key tree splitting elements, across simulation outputs belonging to the seven selected stakeholder satisfaction scenario types. Relative change (percentage) in the intrinsic growth rates (r) from their original values (r_0), for the key social-ecological system elements allowing to differentiate between the seven main stakeholder satisfaction scenario types, based on the structure of the classification tree (Fig. 3). Box plots show the relative changes from r_0 for the r values of SES elements that differentiated the scenario type from the others through tree splits. The median (vertical line), 25th and 75th percentiles (interquartile range; box boundaries), minimum and maximum values (end of the whiskers at either side of the box) and outliers (dots beyond 1.5 × interquartile range) are displayed, for the true positives only (i.e., simulation outputs truly belonging to the satisfaction scenario predicted by the tree). The dashed vertical line at 0 represents no change in growth rate ($r = r_0$), with values to the left indicating negative changes and those to the right indicating positive changes. Stakeholder satisfaction scenario types are associated to the following colours: teal for the "agriculturalist-only", green for the "conservationist-only", orange for the "entrepreneur-only", red for the "endogenous development only" and yellow for the three "all-inclusive" scenario types.

abandonment. Moreover, the r values of *services GDP*, *salary in agriculture* and *tourism establishments*, all related to the economy, and *summer seasonal population*, linked to economy and demography, also emerge as key. Other studies of drivers of social-ecological change in European mountain areas yield similar results. For instance, Muñoz-Ulecia et al.[39] identified factors driving the evolution of cattle farming systems in the Aragonese Pyrenees over the last 30 years. Policy and socioeconomic drivers (mainly the European Union's Common Agricultural Policy (CAP)) were the most important at European level, while economic and household drivers (the development of tourism and household characteristics, respectively) were the most influential at regional level. A study of environmental and social drivers affecting value chains in 23 European mountain regions found that climatic drivers (temperature and precipitation) were perceived by stakeholders as the most relevant ones across mountain regions, while demographic drivers were identified as having the greatest impact on the systems[40]. Lecegui et al.[41] studied forest grazing dynamics in two silvopastoral SESs in the pre-Pyrenees, based on fuzzy cognitive mapping involving stakeholders. Their results reveal common external drivers across both systems, such as the CAP and climate change, and more contextual drivers of change, such as economic drivers. Stakeholders had different perceptions of the importance and impact of common drivers, indicating that their perceptions were contextual. Despite evidence of common patterns and drivers of change across European mountain SESs, further research may be required to obtain a comprehensive understanding of the different shared and distinct factors driving changes across mountain social-ecological systems, and their effects and interactions at different scales, from a broader perspective.

Forest growth was identified as an important driving factor in differentiating stakeholder satisfaction scenarios, as it appears three times in our classification tree. Its prevalence compared to *meadows, bushes, and fields* may be due to its characteristics in the SES model: *forests* are not affected by any other variable, and its abundance only depends on its intrinsic growth rate (r), its self-regulating coefficient, and stochastic variations in the r during simulation runs. By contrast, *meadows, bushes, and fields* are negatively impacted by *roads* and *forests*, which may result in a weaker relationship between its r and simulation outputs. The importance of these two elements was to be expected, as agricultural land abandonment and forest expansion were shared concerns among all stakeholders. Moreover, these concerns were translated into stakeholders' satisfaction criteria through the proportions of the total land use area occupied by these two elements, respectively. Nevertheless, this reflects a trade-off between using land as agricultural fields and pastures or as forests. Indeed, the loss of traditional cultural landscapes across European and Mediterranean mountains is attributable to the processes of agricultural land abandonment and subsequent afforestation[42,43]. Cultural, economic and conservation considerations related to the landscape and its ecosystem services (ES) are often more or less explicitly present in discussions around the sustainable development of rural and mountain areas[44–46]. The management of abandoned agricultural lands is an ongoing debate, despite evidence of landscape heterogeneity resulting from light human activity being more favourable for biodiversity than homogenous forested areas[43]. At a finer level of

Table 1 | Core topics defining the four mental frameworks reflected through SES elements or indicators calculated from relevant SES elements, based on López-i-Gelats et al.[26]

Core topics considered in the SES and associated SES elements	Mental framework			
	Conservationist	Entrepreneur	Agriculturalist	Endogenous development
Biodiversity (*bird abundance*, *butterfly abundance*, *butterfly richness*)	Valued and should be preserved.		Valued, although it is not the main concern.	
Occupation in agriculture			Important in the context of agricultural abandonment.	
Agricultural land abandonment (proportion of land use surface area corresponding to *meadows, bushes fields*)	Not desirable because farming is attributed the role of preserving the landscape, and is valued for this reason.	Great concern, especially because this phenomenon comes along with forest regrowth.	Major threat, as farming is considered to be an inherent part of the landscape and the culture.	Major concern, as the traditional agricultural landscape should be preserved.
Forest regrowth (proportion of land use surface area corresponding to *forests*)	On the one hand, forest regrowth may constitute a threat to agricultural land, but on the other hand, nature-based tourism and wild landscapes are also highly valued.	Great concern.	Great concern, as it is linked to agriculture abandonment.	Considered as a threat to agricultural landscapes. A balance must be found between conservation and agricultural production.
Balance between agriculture and tourism in the economy (ratio *agriculture GDP/services GDP*)	Needed, because mass tourism is seen as a threat.	Priority is given to tourism. The traditional subsistence economy should disappear.	Needed, as agriculture is seen as a major economic asset.	Needed, as economic diversification is important.
Depopulation (*resident population*)		Population loss is a great concern.		Important, but not as big a concern as for the entrepreneur.
Second homes	Seen as a major threat.		Considered as a threat to the traditional way of life.	Major concern.
Subsidies to agriculture		Considered as a weakening factor for the local economy.		
Economic growth (*total GDP*)		Important.		
Urbanisation (*urban areas*)	Very negatively perceived.	Important, as the building industry is considered one of the key promoters of economic growth.	Seen as a threat to the traditional way of life.	Not necessarily rejected *per se*.
Mass ski tourism (*winter seasonal population*)	Very negatively perceived.	Very important promoter of economic growth.	Seen as a threat to the traditional way of life.	Very undesirable and considered as harmful for the local economy.

Cells are coloured depending on the perception and importance of the topic in a mental framework (blue: positive perception/red: negative perception; dark: important aspect/ light: less important aspect). SES elements are denoted in italics, whether these were considered as defining the core topic directly or used for calculating indicators reflecting it better. More details can be found in the Supplementary Methods, and Supplementary Tables 2–4.

detail, our results show that the two "all-inclusive" scenario types with the highest percentage of simulations meeting the criteria for all stakeholders are the only cases where the stakeholders' criteria regarding the proportion of *meadows, bushes, and fields* are met, and the only cases where all biodiversity variables meet their requirements. Moreover, the different types of criteria met are the most balanced across winter tourism, urbanization, economic growth, land abandonment and biodiversity conservation in these two "all-inclusive" scenario types, which are associated with the lowest values of *forest* growth compared to its original value. This suggests that controlling forest expansion is key to supporting what here appears as the most consensual future scenario for the SES.

However, it is not only the extent of agricultural land *versus* forested areas that matters; landscape structure and the intensity of human impact (or use) must also be considered, as these characteristics affect both biodiversity and ecosystem services[47,48]. The homogenisation of the landscape and loss of cultural landscapes in European mountains is partly the result of agricultural intensification and is shaped by multiple drivers[49]. Finding the best strategy to integrate conservation with other priorities in land-use management is a complex endeavour. Some authors have used integrative and interdisciplinary modelling frameworks to study the potential consequences of different land-use scenarios on the landscape and for local people's livelihoods. For instance, Duguma et al.[50] mapped the evolution of the location and extent of woody-plant based ES in southwestern Ethiopia under the different scenarios obtained from workshops with local stakeholders. They found that agricultural intensification would lead to a reduced access to ES and to an increased pressure on forest ES, which were unintended side effects of some of the scenarios evaluated. Our study considers the complex dynamic behaviour of the SES, and interactions at the system's scale. It suggests that these land use issues should be prioritised among other manageable aspects of the system. Continued efforts to understand and to inform policy makers about the complex processes influencing land abandonment are key in European mountains, where the risk of abandonment is higher than in the lowlands[49]. In our case study, a more detailed, spatially explicit analysis could contribute to more specific recommendations for land use planning.

Interestingly, despite divergences in stakeholders' priorities, three different combinations of system conditions could achieve scenarios

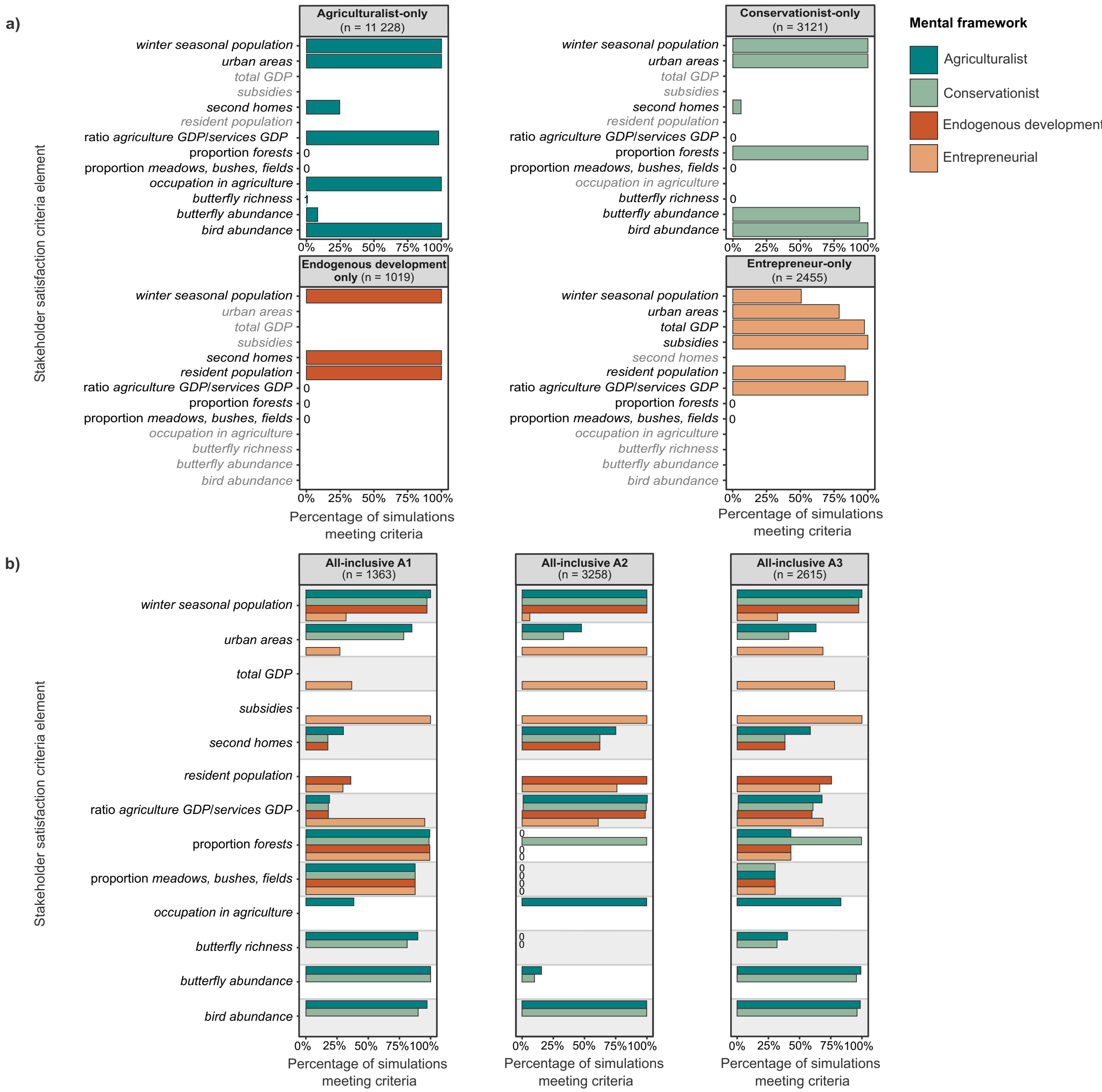

Fig. 5 | Percentage of simulations where the satisfaction criteria are met. **a** Percentage of simulations where the satisfaction criteria are met in the individual satisfaction scenario types ("conservationist-only", "entrepreneur-only", "agriculturalist-only", and "endogenous development only"), and **b** in the three all-inclusive satisfaction scenarios (A1, A2 and A3, see Fig. 3). Stakeholder satisfaction scenario types correspond to the true positives within the subsets obtained after filtering the raw data according to the classification tree predictions for the leaves (see Fig. 3). SES elements and indicators used for defining the corresponding stakeholder satisfaction criteria are shown in black, and in grey if not relevant (see "Methods", Supplementary Methods and Supplementary Tables 2–4 for more details on the satisfaction criteria). Mental frameworks are associated to the following colours: teal for the agriculturalist, green for the conservationist, orange for the entrepreneurial, and red for the endogenous development.

simultaneously satisfying the four mental frameworks. Satisfaction tended to be similar or higher in the "all-inclusive" scenario types than in the individual ones. Balancing multiple stakeholders' interests thus appears as a feasible and likely desirable objective to work towards, and the diversity in scenario outcomes highlights the importance of exploring alternative pathways rather than focusing on a single goal.

All scenario types except for the "endogenous development only" are grouped above the threshold determined by the *r* of *services GDP*. Across these, the next two leverage points are the *r* values of *salary in agriculture* and *forests*. Finding simulation outputs favourable to the agriculturalist below the threshold for *salary in agriculture* may seem contradictory, but can be explained by the negative effect of this variable on *occupation in agriculture*. A balance between the agricultural and the tertiary sectors must be found in most cases, which is consistent with previous findings regarding the need of a balance between economic sectors in the Pyrenean SES[34]. Similarly, focusing on ecosystem services in an Austrian valley in the Alps, Huber et al.[51] found that diversification of the economy was associated with higher landscape multifunctionality, while too high tourism or agriculture intensity both led to a decrease in ecosystem services supply. Tourism constitutes the main pillar of economic growth in our region, hindering the system's resilience to potential crises, and increasing the pressure on water resources, especially in summer[34]. While the *r* of *services GDP* appears at the top of the tree, factors more explicitly linked to tourism play a more specific differentiating role. Economic growth based on the tertiary sector *per se* does not seem to be especially divisive, but tourism certainly appears to be a more contentious issue, mirroring the divergence of views on mass tourism in the Pyrenees[26]. Socio-economic changes such as the shift from agriculture to tourism, and the increasing demand for outdoor recreation, are at the root of most conflicts around cultural ecosystem services of mountain landscapes[52]. Residents' support to tourism policies depends on their perceptions of environmental, economic and socio-cultural impacts of tourism and on their personal economic dependency to tourism[53]. In this regard, not all scenario types are associated with a balance in the economy. Results regarding the "entrepreneur-only" scenario type emphasise economic growth and prioritising tourism. In their study characterizing socio-economic tipping points, van Ginkel et al.[54] identified the collapse of winter sports tourism in lower-altitude ski resorts and agricultural decline and abandonment as two climate change induced socio-economic tipping points. These tipping points, most evident at regional to smaller scale, are highly relevant for European policies defining mitigation and adaptation strategies[54].

In the "conservationist-only" scenario type, this stakeholder's mental framework criterion regarding the balance between *agriculture* and *services GDP* is not met in any of the simulations, possibly due to the negative relationship between *occupation in agriculture* and *salary in agriculture*. Or, considering the SES network structure as well as the conservationist-related results, where tourism is temporally less concentrated in winter and forest expansion is not refrained, another possibility could be to interpret this scenario type as one compatible with a year-round, nature-based touristic model. However, the diversification of the touristic offer can be done in many ways, not necessarily aligned with the four mental frameworks[14]. To avoid irreversible harmful effects on both societies and ecosystems, social-ecological tipping points should be recognised and addressed in mountain SESs governance and management strategies, as should also be the views of local communities.

Our dynamical model assumes linear relationships among SES elements and does not include feedback loops other than self-regulation coefficients, nor cross-scale interactions. These simplifications, which may limit the model's ability to capture emergent behaviours and nonlinear dynamics of the system, were necessary in the scope and practical constraints of this study to manage the complexity of incorporating 30 variables and their interactions. Moreover, whereas the model was parametrised using empirical data, its structure was validated through the previous path analysis performed by Zango-Palau et al.[34], and model output behaviour validated by graphical comparison with observed system data, further improvements could be undertaken to improve the fidelity of the dynamical model to the real system. Additionally, qualitative discourses identified by López-i-Gelats et al.[26] were translated into quantitative criteria to represent mental frameworks. While these criteria align with established local priorities, they may not fully reflect current concerns in the study area. Together, these simplifications and assumptions frame our study as exploratory.

Our results generate testable hypotheses and highlight key areas of the system where data collection or research efforts should be focused, if or when additional data becomes available. Future studies could build on this framework by selectively integrating feedback loops and non-linear relationships, by further developing the dynamical model to improve representational detail and accuracy[32], and by engaging stakeholders more directly in the modelling process. Further versions of the dynamical model could also potentially enable the exploration of leverage points *sensu* Meadows[55].

In summary, we identify key elements driving a mountain social-ecological system from the Pyrenees towards development pathways that satisfy different local stakeholders' mental frameworks. Socioeconomic and land-use factors were identified as the main influential factors intervening in trade-offs between stakeholder interests. Economic diversification and addressing trade-offs in land use emerge as essential to support sustainable development in this SES. The multi-stage modelling framework employed here facilitates putting forward major elements of discussion to be carefully evaluated when planning and implementing policies or development strategies in a complex SES. Results also show that various combinations of conditions can lead to scenarios that satisfy all coexisting mental frameworks. Engaging with stakeholders throughout the modelling process could contribute to enhancing the relevance and applicability of this approach to specific contexts.

Methods

Case study

We focus on a Pyrenean SES located in the upper Segre River watershed[34], encompassing the Catalan counties of Alt Urgell and La Cerdanya (1993 km^2) in northeastern Spain (Fig. 2a). The original network model representing this SES comprises 13 socioeconomic, 4 land-use, 4 biodiversity-related, 4 hydrological, 2 climatic, and 4 remote-sensing-derived environmental elements, resulting in a total of 31 interacting social-ecological elements (Fig. 2b and Supplementary Table 1, Supplementary Methods). Interactions between elements were defined using expert knowledge and evidence from the literature. Empirical data from annual time series between 2000 and 2020 for the SES variables in the study area obtained from public databases were used to quantify the interactions[34]. Interaction strengths were quantified using a piecewise structural equation model fitted to the temporal data and incorporating the inferred relationships between variables using the R package *piecewiseSEM*[56].

To define the extent to which local stakeholders may value different aspects of the SES and how the system could evolve, we used evidence from four mental frameworks previously identified in the Pyrenees[26] (Fig. 2c). These correspond to four different views and perspectives on development and were found to differ with respect to different core topics such as biodiversity conservation, farming, tourism, and the traditional landscape (see Table 1 for a full qualitative description of the mental frameworks, and Supplementary Methods and Supplementary Tables 2–4 for the quantitative characterisation):

1. The conservationist values primarily ecological assets, both for their intrinsic value and the ecosystem services they provide. Farming is also given importance for its role in preserving the landscape.
2. The entrepreneur gives priority to economic growth and counteracting local depopulation. Development based on ski tourism and construction appears as the means to fulfil these objectives.
3. The agriculturalist advocates for putting agriculture back at the forefront of the development agenda. Not only is agriculture valued for cultural reasons, as agricultural landscapes are important for local people's identities and attract tourism, but it is also seen as a major economic asset for its productive role.
4. The endogenous development primarily focuses on the negative repercussions of the current development model, based on tourism and second housing, and resulting from governance processes not fitted to the local context.

Modelling approach

We adopted a modelling approach involving six stages to model the Pyrenean SES as a dynamical system, run simulations and analyse the complex simulation outputs to identify key factors associated with the satisfaction of different stakeholders' mental frameworks (Fig. 1).

In the first stage, we specified the structure of the SES as a network of relationships between the socioeconomic and ecological elements of the Pyrenean system following Zango-Palau et al.[34] (Figs. 1 and 2b). All SES elements correspond to measurable indicators quantifying second-tier variables defined in Ostrom's SES framework[3,57] (Supplementary Table 1 and Supplementary Fig. 1, Supplementary Methods). To quantitatively characterise any given state of the Pyrenean SES as fitting the four stakeholders' priorities, we defined stakeholder satisfaction criteria tailored for the SES (Fig. 2c and Table 1 Supplementary Methods). Whenever possible, the distinguishing statements used to identify the conservationist, entrepreneurial, agriculturalist and endogenous development discourses in López-i-Gelats et al.[26] were directly or indirectly associated to elements of the SES model developed in Zango-Palau et al.[34]. (Supplementary Tables 2 & 3). Based on the scores associated to the statements, we established favourable ranges of values for the selected SES elements (*bird abundance*, *butterfly abundance*, *butterfly richness*, *occupation in agriculture*, *resident population*, *second homes*, *subsidies to agriculture*, *total GDP*, *urban areas* and *winter seasonal population*), or indicators calculated from SES elements (the proportion of *meadows, bushes, and fields* and of *forests* compared to the total land use area, the ratio *agriculture GDP/services GDP)*, for each of the mental frameworks (see Supplementary Table 1 for the description of the SES elements, and Table 1, Supplementary Methods and Supplementary Table 4 for their use in defining the mental frameworks' satisfaction criteria).

In the second stage, a dynamical network model grounded on ordinary differential equations (ODEs) of the SES was implemented. The model included nodes and interactions between system elements from the SES network. This resulted in $N = 30$ elements out of 31 being retained (see Supplementary Methods for details, and Supplementary Fig. 2 for a visual representation of the resulting network topology). We modelled the rate of change per unit time in the value of any given element of the SES as follows:

$$\frac{dX_i}{dt} = X_i\left(r_i\varepsilon_i + a_{ii}X_i + \sum_{j=1}^{N} a_{ij}X_j\right), \qquad i = 1, \ldots, N \qquad (1)$$

Where:

- X_i represents the value of SES element *i*.
- r_i is the intrinsic growth rate of the SES element, representing the part of the growth (or decline) in element *i* that is not due to interactions with other elements.
- $\varepsilon_i \sim U(0.95, 1.05)$ is a stochastic term, adding random variation to r_i at each time step of the simulation. A new value of ε_i is randomly sampled at every time step of a simulation.
- a_{ii} is a self-regulation coefficient depicting the effect of element *i* on its own growth. Self-regulation coefficients were added to improve stability of the system, as otherwise some SES elements increased to infinite values in the simulations.
- a_{ij} represents interaction coefficients between elements *j* and *i*, encapsulating the effect of *j* on *i*. These are analogous to the interaction coefficients found with piecewiseSEM in Zango-Palau et al.[34].

The same dataset as in the *piecewiseSEM* analysis done by Zango-Palau et al.[34] was used for parameter estimation. However, to avoid convergence issues in the simulations, all the values of the SES elements were divided by factors of 10 until showing a similar range, within *ca.* 0 and 3, thus matching the small ranges of *roads* and *max summer NDVI* (normalized difference vegetation index) (see conversion factors in Supplementary Table 1). The model was parametrized by fitting a linear regression of the per-unit growth rate to the data, or relative growth rate $\frac{dX_i}{X_i dt}$ of element *i* against SES elements values as shown in Eq. (2).

$$\frac{dX_i}{X_i dt} \sim r_i + a_{ii}X_i + \sum_{j=1}^{N} a_{ij}X_j \qquad (2)$$

One linear model was fitted for each of the 30 elements in the system, with their respective predictors, based on the static SES network structure (Supplementary Table 5). This enabled the estimation of the parameters of the dynamical SES model as statistical parameters: r_i as the intercept (Supplementary Table 6), and a_{ii} and a_{ij} as the regression coefficients (Supplementary Table 7). Additional details on model specification and parametrization can be found in the Supplementary Methods.

During the third stage, we ran 100,000 numerical simulations of the model in Eq. (1) using the *deSolve* R package[58], to explore the behaviour of the system under a wide range of varying combinations of values of intrinsic growth rates (*r* values). We sampled *r* values for the system's elements from uniform distributions within a range of variability of 50% around the values estimated from the linear regression (Eq. (2); i.e., $U(r_i - .5r_i, r_i + .5r_i)$) using Latin hypercube sampling with the R package *lhs*[59]. Hypercube sampling ensures uniform exploration of the n-dimensional parameter space given by the intrinsic growth rates of all system elements as dimensions. Initial conditions (i.e., starting values) of the SES elements were assigned the values observed for each of the elements in 2020 (last observations of the time series data).

Simulation outputs were assessed by quantifying the median value of each SES element in the last 10 time steps of the simulations. These outputs were processed to retain only physically possible final values for the variables: cases where (1) the sum of all land use output values did not exceed the real total land use surface area calculated from the raw data, allowing for a 10% decrease from this value to account for land use categories not included as elements of the SES; (2) *max summer NDVI* output values remained in the range $(-1, 1)$; and (3) no element outputs showed negative values except *max summer NDVI* and the temperatures. Additionally, this initial set of simulation outputs was used to perform the operational validation of the model, by graphically comparing the distribution of simulation output data with the distribution of the observed data (Supplementary Methods, Supplementary Fig. 3).

To assess whether a given simulation output was favourable to a given local stakeholder, we used the satisfaction criteria described above (Table 1 and Supplementary Table 4 and Supplementary Methods). To accumulate enough realistic stakeholder satisfaction scenarios, we considered a given output to be favourable to a mental framework when it fulfilled at least 50% of the criteria of satisfaction for said framework.

We considered five possible satisfaction scenarios: the four cases where only one mental framework is satisfied (called "conservationist-only", "entrepreneur-only", "agriculturalist-only" and "endogenous development only"), and the case where all four are satisfied (called "all-inclusive"). The great majority of simulation outputs (72%) belonged to the "all-inclusive" scenario, and no simulation output corresponded to the "endogenous development only" scenario.

Building on the output set from stage three, additional simulations were performed in a fourth stage, attempting to balance the number of simulations across satisfaction scenario classes as much as possible, to avoid a biased classification in the fifth stage. In these additional simulations, the combinations of *r* values of each run were sampled within ranges of *r* values already obtained in previous runs for the target stakeholder satisfaction scenario to be balanced out compared to the "all-inclusive" scenario. This final output set comprised a total of 91,019 simulations: 20% belonged to the "conservationist-only", 19% to the "entrepreneur-only", 32% to the "agriculturalist-only, 2% to the "endogenous development only" and 27% to the "all-inclusive" scenario (Supplementary Methods).

Analyses of simulation outputs

In the fifth stage, we used a classification tree model to identify the specific key combinations of SES elements' *r* values differentiating the five stakeholder satisfaction scenarios. The response or target variable was the stakeholder satisfaction scenario describing the compatibility of the simulations with the stakeholders' mental frameworks. Predictor variables or features were the intrinsic growth rates of all SES elements, excluding those used in the stakeholder satisfaction criteria and that of roads (the dynamics of *roads* were artificially constrained when manually setting its self-regulating coefficient manually to -1 to prevent exponential growth). A classification tree uses the values of the features to hierarchically divide a complex dataset into homogenous subsets of data (i.e. the leaves of the tree) where each subset ideally corresponds to a specific class of the target variable. This analysis provided a better understanding of the boundary conditions across *r* values that associate with the satisfaction of specific stakeholders' mental frameworks. The *caret* package[60] in R was used for data partitioning, hyperparameter optimization with repeated stratified cross-validation with undersampling, and model fitting and evaluation. We compared several classification algorithms, including *rpart*, *rpart2*, *ctree* and *ctree2*. Models were tuned to optimize hyperparameter values using the same data partitions and repeats (Supplementary Methods and Supplementary Table 8) and were compared based on their average performances across

cross-validation resamples within the training set and on model complexity (Supplementary Table 9 and Supplementary Fig. 4, see Supplementary Methods for further details). Based on these criteria, the *rpart* model was selected as the final model (Supplementary Table 9 and Supplementary Fig. 5). The confusion matrix and statistics by stakeholder satisfaction scenario class for test data prediction for the *rpart* model trained on the full training set can respectively be found in Supplementary Tables 10 and 11.

When patterns in the data are complex, the partitions predicted by a classification tree do not usually result in completely homogenous leaves (e.g., a leaf predicted to be "conservationist-only" by the tree may not actually comprise only simulations belonging to this class, but also to other stakeholder satisfaction scenarios). To address this, in a sixth and final stage, the raw simulation output data were first divided into subsets based on the partitions found by the classification tree, resulting in subsets analogous to the leaves of the tree. Each subset was then refined by retaining only those simulation outputs where the actual stakeholder satisfaction scenario class matched the predicted class in the tree (i.e., true positives). This enabled us to determine the quantitative range of values that the r of the key boundary elements identified by the tree should have to enable the realisation of each scenario. Further, it allowed for the comparison of these ranges of r values with their original value (intercept in the linear models fitted to the data). The relative change from the original r value (r_0) was calculated as $\frac{r_{\text{simulation}}-r_0}{|r_0|}$ x100 (Supplementary Methods). These completely homogenous subsets of data equivalent to the true positives within the leaves of the tree are called here "stakeholder satisfaction scenario types". Since the classification tree was relatively complex (13 leaves, see Supplementary Fig. 5), we focused on what were considered the 7 most relevant and representative stakeholder satisfaction scenario types. Only the cases where true positives constituted at least 50% of the simulation outputs in the subsets analogous to the leaves were retained in the case of the "conservationist-only", "entrepreneur-only" and "agriculturalist-only" scenario types. This resulted in one stakeholder satisfaction scenario type each. There was only one possible subset in the case of the "endogenous development only", in which this class represented only 20% of simulations. Finally, all three subsets corresponding to the "all-inclusive" scenario were retained, labelled A1, A2 and A3 to differentiate them.

The model, simulations protocol and classification tree analysis were implemented in R version 4.3.1[61].

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data and R code to reproduce the results of this study are available in the CORA repository[62]: https://doi.org/10.34810/data2168.

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Author contributions

Anaïs Jolivet, Miguel Lurgi and Bernat Claramunt-López conceived and designed the project. Anaïs Jolivet performed the modelling work with assistance from Miguel Lurgi. All co-authors discussed the results. Anaïs Jolivet wrote the first draft of the manuscript, and all co-authors contributed to revisions.

Competing interests

The authors declare no competing interests.

Additional information

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