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Modelling system dynamics as a socio-ecological perspective to support human-beaver interactions

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ABSTRACT

Beavers are semi-aquatic mammals that significantly impact on freshwater ecosystems, creating benefits and challenges, particularly in areas with close human interaction. Managing human-beaver interactions is a multifaceted issue due to the many variables involved, but the complexity of these interactions can be analysed effectively using system dynamics models. These models are used in many contexts, including wildlife management, to simulate a variety of management policies and assess their effects. The present study addressed gaps in the literature by developing a system dynamics model that examined both the benefits and conflicts that arise from human-beaver interactions. The model, implemented using Vensim PLE software, synthesised qualitative and quantitative data to simulate four simulation scenarios: ecological, social, economic, and policy making. The study examined the dynamics of beaver populations, ecosystem service provision, social perceptions, and management strategies in a case study of the Ivrea lakes area in the Piedmont region (Italy). Model predictions highlights that beaver populations stabilized logistically, influencing ecosystem services and residual capital, while social acceptance stongly reduced management costs and social pressure. Optimal budget allocation and combined strategies emerged as key to sustainable management and conflict mitigation. Overall, predictions suggest that an integrated approach that prioritises prevention and actively engages local communities can improve both ecological outcomes and social acceptance of beavers. The model is a useful decision and discussion tool for assessing management strategies and facilitating stakeholder involvement. Future studies should expand on these results by exploring additional beaver-related conflicts and benefits in diverse contexts.

1. Introduction

Wildlife management is complex due to the variety of ecological, social, and economic factors involved (Bhatia et al., 2020), whose dynamic interactions require a holistic approach that recognises system complexity and can assess relationships among multiple variables (Lischka et al., 2018). System Dynamics (SD) models have emerged as a valuable tool to support wildlife management because they can capture complex relationships and feedback loops in ecological systems (Ford, 2010; Grant et al., 1997; Sterman, 2000). Specifically, SD identifies and visualises key variables and qualifies or quantifies their interconnections in complex systems (Lin et al., 2020; Sterman, 2000). Applying SD combines scientific modelling, ecological knowledge, and practical management strategies to provide a scientific foundation to understand ecological dynamics, predict results of management practices, and guide decision-making by exploring scenarios (Forrester, 1994; Turner, 2020). SD was developed in the 1950s by Professor J.W. Forrester of the Massachusetts Institute of Technology and initially applied almost exclusively to business management (Forrester, 1987). Currently, SD is used to address challenges in multiple contexts, such as environmental protection (Bozorg-Haddad et al., 2022; Ding et al., 2018), use of natural resources (Vance et al., 2022), education (Eidin et al., 2024), public health (Davahli et al., 2020), urban planning (Diemer and Nedelciu, 2020), policy design (Groff, 2013), social changes (Hirsch et al., 2007) and business and management (Ismail et al., 2022; Sterman, 2000).

Regarding wildlife management, SD is increasingly used to analyse population dynamics, assess impacts of habitat change, assess conservation status and strategies, and mitigate human-wildlife interactions and conflicts (Lopes and Videira, 2017; Patana et al., 2021; Qudrat-Ullah, 2023). These applications have focused on a variety of wildlife species, such as sage grouse (Beall and Zeoli, 2008), African penguins (Weller et al., 2016), African elephants (Velempini, 2021), black bear

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(Siemer and Otto, 2005), tigers (Patana et al., 2021; Rieder et al., 2021), goose barnacles (Bald et al., 2006) and Manila clams (Bald et al., 2009). Thus, the use of SD helps to manage the ecological and social complexity of wildlife management and understand and predict non-linear relationships among species, the environment, and human activities (Berrio-Giraldo et al., 2021). Therefore, SD could be particularly useful for managing species that live close to humans, such as beavers.

Beavers are semi-aquatic mammals known as ecosystem engineers due to their ability to deeply modify the local environment through their behaviour (Brazier et al., 2021; Grudzinski et al., 2022; Roper, 2022; Rosell and Campbell-Palmer, 2022; Svanholm Pejstrup et al., 2023). The main beaver activities are lodge construction, canal digging, tree felling, and damming (Rosell et al., 2005; Rozhkova-Timina et al., 2018; Stringer et al., 2015). These activities have multiple effects on ecological, hydraulic and hydrological, climatic, and socio-economic dimensions (Brazier et al., 2021; Rosell and Campbell-Palmer, 2022; Rozhkova-Timina et al., 2018; Thompson et al., 2021). Beavers usually live in freshwater environments surrounded by woods, such as floodplains, rivers, streams, and lakes, but they can establish populations in suboptimal habitats, such as agricultural canals, suburban areas, and urban areas due to their adaptability (Bailey et al., 2019; England & Westbrook, 2021; Romanowski & Winczek, 2018; Taylor et al., 2017). In human-dominated environment, beaver needs and behaviours often collide with human activities, creating interactions. These interactions frequently lead to the insurgence of conflicts due to the impacts of beaver on human activities, such as tree damage, crop damage, and flooding of farmland and infrastructure (Campbell-Palmer et al., 2016; Taylor et al., 2017; Treves et al., 2020). However, these conflicts are not solely the result of beaver behaviour; they depend on how humans perceive and respond to these impacts. Key factors influencing human responses include the nature of interactions, risk perception, resource dependence, social interactions, and value orientations (Bhatia et al., 2020). The conflicts can cause human to perceive beavers as pests (Coz and Young, 2020), which obscures benefits of co-existence and complicates beaver management.

Currently, beaver management is no longer aimed only at managing conflict but includes a participatory perspective that aims for coexistence between human and beavers (Treves and Comino, 2023). Several studies have investigated human perceptions of beavers and beaver management, but it appears that only one study has used SD to explore beaver management, despite its known potential for wildlife management: Siemer et al. (2013) developed a causal loop diagram (CLD) of urban beaver management based on results of a survey. CLD qualitatively map direct causal relationships among the key variables, and it consists of multiple variables and directional links (i.e. arrows) based on initial hypothesises (Lin et al., 2020; Sterman, 2000). The CLD of Siemer et al. (2013) qualitatively represented relationships among stakeholder responses, norms, and management practices in relation to an increase in beaver density. Moreover, it conceptualised beaver management as a coupled human-natural system by showing how stakeholders' attitudes and responses can influence typical beaver management and density. However, two gaps in that study stand out: Siemer et al. (2013) (1) focused mainly on negative stakeholder perceptions of beavers and ignored positive experiences related to ecosystem services that beavers provide in freshwater ecosystems, and (2) explored the key dynamics of beaver management from a conceptual viewpoint and did not simulate scenarios to assess dynamics of the system quantitatively.

To fill these gaps and embrace a socio-ecological management perspective of wildlife, the present study aimed to develop a SD model of human-beaver management. The model qualitatively and quantitatively assesses the complexity of the management of human-beaver interactions through a socio-ecological lens, by (1) not focusing only on conflict management, (2) considering ecosystem services that beavers provide, (3) quantifying relationships in the system, and (4) predicting effects of management practices to guide decision making. Although the model was designed to be applicable to any study area, a case study area in the Piedmont region (Italy) was selected to quantitatively assess the key dynamics of beaver management.

2. Description of the case study area

The case study area was the Ivrea lakes area (42.33 km^2) in the province of Turin in the Piedmont region of north-western Italy (Fig. 1). This area is part of the administrative territory of the province of Turin and it extends between latitudes 45°27′36″ N – 45°31′12″ N and longitudes 7°49′51″ E – 7° 54′ 58″ E. It includes the city of Ivrea, the Dora Baltea River, five lakes, surrounding municipalities, as well as a European Union Site of Community Importance surrounded by a human-made zone. Thus, this area is important ecologically but also hosts several human activities.

The area currently contains no beavers, but Treves et al. (2022) did identify several suitable habitats along freshwater environments (ca. 0.65 km^2) where Eurasian beavers (*Castor fiber*) could be reintroduced. The suitable area increased to 2.2 km^2 if areas up to 40 m apart were considered to be interconnected (Treves et al., 2022) (Fig. 1b), and this area was estimated to have the potential to support a population of 6–20 beavers (Treves et al., 2022).

3. Materials and methods

3.1. Theoretical background of system dynamics

System Dynamics is an effective approach for understanding the dynamics of complex systems over time (Sterman, 2000) by focusing on feedback loops, delays, and nonlinear relationships that influence system behaviour (Sterman, 2000). SD models are developed in five phases according to Sterman (2000). First, the problem is defined based on a literature review, interviews, or surveys. Second, the system structure is conceptualised using Causal Loop Diagrams. Each link between variables has a positive or negative sign depending on whether the variables have the same or opposite cause-effect direction, respectively (Lin et al., 2020; Sterman, 2000). The loops are classified as reinforcing, which amplify dynamics (due to positive polarities or an even number of negative polarities), or balancing, which counteract dynamics (due to an odd number of negative polarities). Third, system variables are mathematically defined by identifying stocks, flows, constants, and auxiliary variables. Stocks and flows are fundamental for understanding dynamics of complex systems because they allow dynamics to be assessed quantitatively. Stocks represent the accumulation of materials, energy, or information over time through the action of one or more flow variables (Hirsch et al., 2007). In the stock and flow diagram, rectangles represent stocks, and arrows into or out of rectangles represent flows, which are controlled by valves. Flows originate and terminate in clouds which represent sources and sinks (Sterman, 2000). In addition, auxiliary variables are functions of stocks, constants, and/or exogenous inputs (Sterman, 2000). Fourth, the consistency and robustness of the SD model is tested under extreme conditions. Finally, scenarios are defined based on potential policies and simulated over time. In this way, it is possible to understand policies' effects, their interactions, their synergies, and responses needed to manage the problem studied (Homer and Hirsch, 2006).

3.2. Study design and application

To qualitatively and quantitatively assess the key dynamics of the management of human-beaver interactions, a SD model was developed by following the phases described above (Fig. 2) and using the open-source version of Vensim® software (i.e. Personal Learning Edition (PLE), Ventana Systems, Inc., Harvard, Massachusetts, USA). Vensim PLE is an easy-to-use simulation software that is used to visualise real systems and improve their performance through simulation.

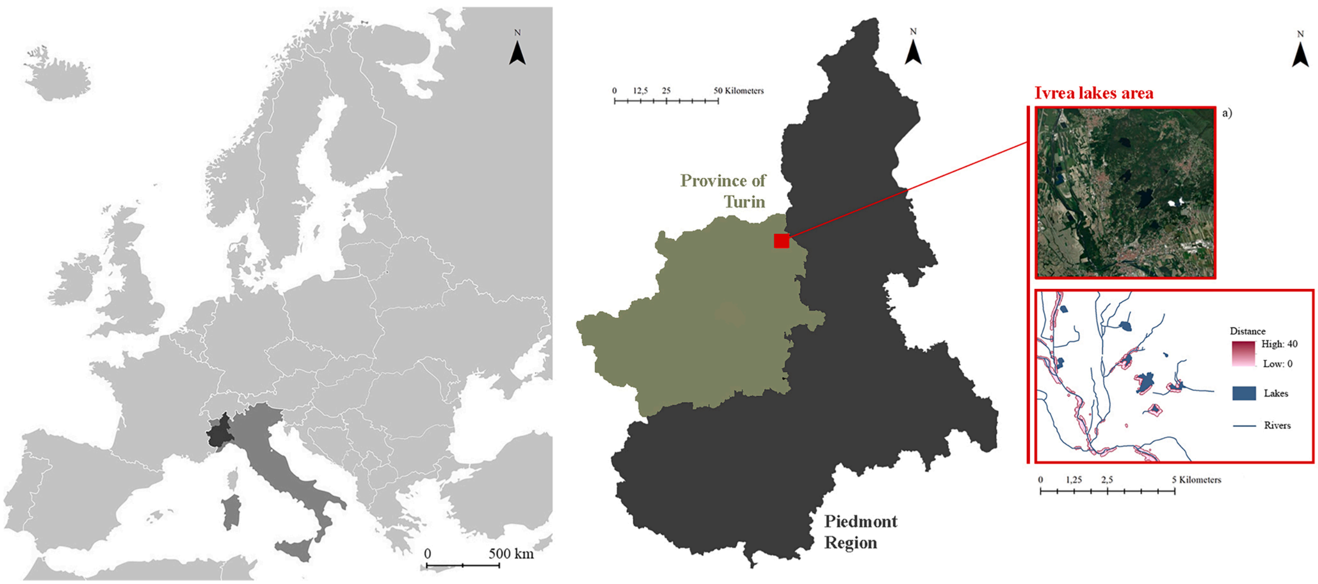

Fig. 1. Location of the case study area, the Ivrea lakes area (red), located in the province of Turin (olive green) in the Piedmont region (45° N, 8° E; black) of Italy. The Ivrea lakes area is presented in a (a) satellite map and (b) map of interconnections between areas suitable for beavers (adapted from Treves et al. (2022)).

Fig. 2. The six phases of developing the system dynamics model.

3.2.1. *Phase 1 – problem definition*

In phase 1, a framework for developing the SD model was created that defined the problem related to beaver management based on publications about human dimensions in an in-depth literature review (2018–2023) in a previous study (Treves and Comino, 2023). After investigating these publications thoroughly, nine of them were selected that described studies that assessed people's perceptions of beavers and their management using a variety of methods. For each publication, the stakeholders involved and their perception of and/or attitudes towards beavers were identified (Table 1). Analysis of this information enabled three human attitudes towards beavers to be identified: beaver-accepting (favourable to beavers and conscious of the ecosystem services they provide), beaver-managing (favourable to beavers but conscious of the need for planned management to address both positive and negative impacts), and anti-beaver (unfavourable to beavers and requiring their removal due to the damage they cause). These three attitudes represented the framework of beaver management and highlighted the need to investigate its complexity by focusing on conflicts and benefits of beaver presence.

3.2.2. *Phase 2 – variable identification and causal loop diagram*

In phase 2, the three attitudes were used to identify eight variables involved in managing human-beaver interactions: the beaver population, ecosystem services provided, negative impacts or damage, beaver removal, preventive measures, damage compensation, information and training sessions, and the budget for management. Identification of these variables and their relationships led to the creation of the CLD (Fig. 3), which provided an overview of the key dynamics by considering the beaver not only as a problem but as a tool. At this stage, the CLD provided an overview by referring to general conflicts and ecosystem services that beavers could generate.

The resulting CLD had five main feedback loops:

- Population management: a balance loop that describes dynamics of the beaver population related to the removal of individuals as a management practice. This loop counteracts the natural growth of the beaver population.
- Ecosystem services: a reinforcing loop that supports an increase in the beaver population. The dynamics influenced by public attitudes to beavers, which result from prejudice, peer effects, and effects of management practices (i.e. damage compensation, information and training, and preventive measures). This loop is often hidden to non-practitioners, but once considered, it compensates for beaver damage by increasing the natural capital and thus economic capital of the area.
- Damage compensation: a reinforcing loop related to monetary compensation for beaver damage.
- Information and training: a reinforcing loop related to information and training initiatives that promote coexistence and minimise anti-beaver attitudes.

Table 1
Publications that assessed human perceptions of beaver impacts and their management, specifying the stakeholders involved and their perception of or attitudes towards beavers.

Publication	Stakeholders involved	Perceptions of or attitudes towards beavers
Auster et al. (2020)	The general public and organisations/ representatives potentially interested in reintroducing beavers	Respondents who worked in the "Farming and Agriculture" or "Fisheries and Acquaculture" sector who were retired and owned property that extended up to/included a watercourse or who were residents of eastern Scotland had less a positive view of beaver impacts. In contrast, respondents who worked in the "Environment, Nature and Wildlife" or "Arts, Sport and Media" sector were significantly more likely to be more positive, as were those who were residents of north-western England. There was an increased risk of polarisation and conflict between these groups. Respondents differed in their level of knowledge. Strong knowledge of beaver ecology influenced a positive view of beaver impacts and support for several forms of management. Only a few respondents were in favour of no management.
Coz and Young (2020)	Representatives of organisations and groups involved or interested in reintroducing beavers and knowledgeable informants	All interviewees highlighted beaver management as a potential issue, specifically the need for appropriate funding for management and monitoring of beaver numbers, expansion, and impacts. A lack of planning and regulation of beaver reintroductions, as well as a vague response from institutions, influenced stakeholder attitudes toward beavers and fuelled conflicts.
Ulicsni et al. (2020)	Inhabitants knowledgeable about beavers and randomly selected locals	Impacts of beavers on provisioning ecosystem services was perceived as negative by the two groups interviewed due to the felling of shade trees or damage to garden plants. Knowledgeable inhabitants mentioned positive impacts more often.
Yarmey and Hood (2020)	Key informants who had direct interactions with beavers (i.e. lived near them, were impacted by them, or managed them)	Experiences of beaver-related impacts varied among individuals. Most of the farmers interviewed considered beavers incompatible with an agricultural lifestyle, and conflicts concerned not only beavers, but also government management decisions. Participants highlighted positive and negative impacts of beaver presence and activity.
Auster et al. (2021)	Members of the fishing community	Three attitudes were distinguished: beaver-accepting (emphasises potential opportunities of reintroducing beavers), beaver-apprehensive (defends tradition, rights, and the ability to fish, considering beavers a threat), and managed-beaver (accepts the potential of beavers, but recognises the need to manage their negative impacts).
Auster et al. (2022, 2023)	People living downstream of three beaver sites	Two attitudes were distinguished: pro-beaver, which was subdivided into ecocentric vs. anthropocentric visions (the latter which highlighted beavers' economic importance and potential to increase tourism), and anti-beaver, which emphasised beavers' negative impacts and the need to manage them.
Oliveira et al. (2022)	The general public, farmers, and people who worked in environmental and wildlife organisations	Attitudes did not differ greatly: respondents felt that beavers had positive impacts and supported different beaver-management measures. More than 25% of participants disapproved of any type of management to mitigate beaver impacts or control beaver populations. The management measures supported most were tree protection, exclusion fencing, flow-control devices, and riparian buffer zones. Trapping for translocation, dam removal, fertility control, and lethal control received little support.
Kohler et al. (2023)	Local residents	The objective impacts of beaver activity is viewed positively or negatively, depending on what perspective and information people had.

- Preventive measures: a reinforcing loop that highlights effects of implementing preventive measures to decrease damage and change public perceptions of beaver behaviour.

All loops except for the ecosystem services loop strictly depend on the amount of capital invested by the public administration to manage human-beaver interactions.

3.2.3. Phase 3 – focus on one conflict

In phase 3, one conflict (i.e. flooding events caused by beaver dams) and one ecosystem service provided (i.e. moderation of extreme events such as floods or droughts) were identified to analyse relationships among the variables and simulate a real system by considering beavers as a Nature-based Solution to ecological restoration of freshwater ecosystems.

3.2.4. Phase 4 – definition of stocks, flows, auxiliary variables, and equations

In phase 4, the relationships were defined mathematically. The SD model contained two stocks: *beaver population* and *residual capital*. The *beaver population* was modelled using logistic population growth as a function of carrying capacity and depends on the inflow *birth* and outflow *death*. The *residual capital* is the amount of capital that remains during a given month of the simulation and depends on two inflows (i.e. *budget* and *economic value of moderation of extreme events*) and one outflow (i.e. *capital used*) (Fig. 4).

Once the model structure was defined, each variable was described as a parameter estimate or equation (applied to auxiliary variables and flows). Moreover, the initial condition of each stocks was set. Variable

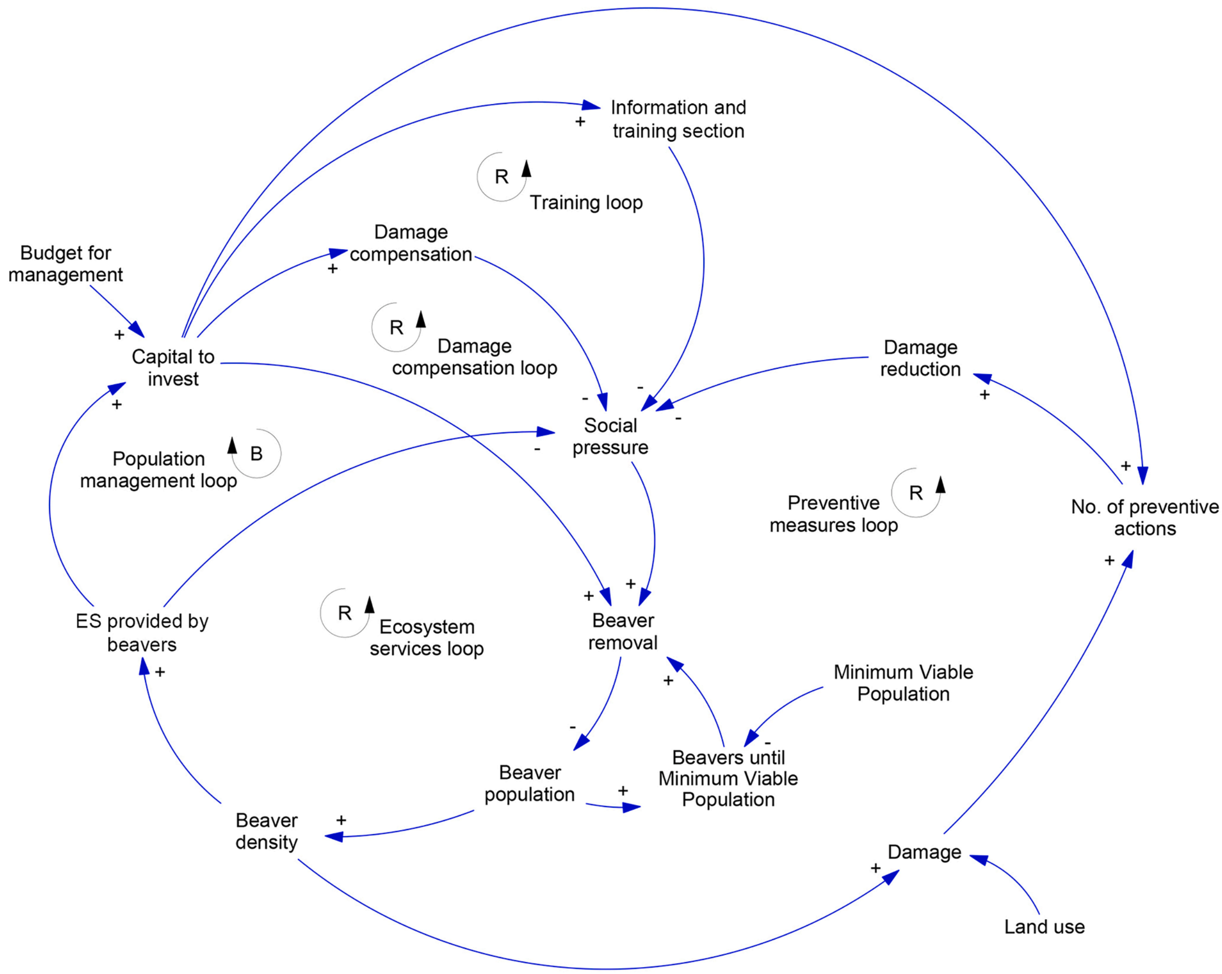

Fig. 3. Causal loop diagram of the key dynamics of beaver management, including conflicts and ecosystem services (ES) provided. R: reinforcing loop, B: balancing loop.

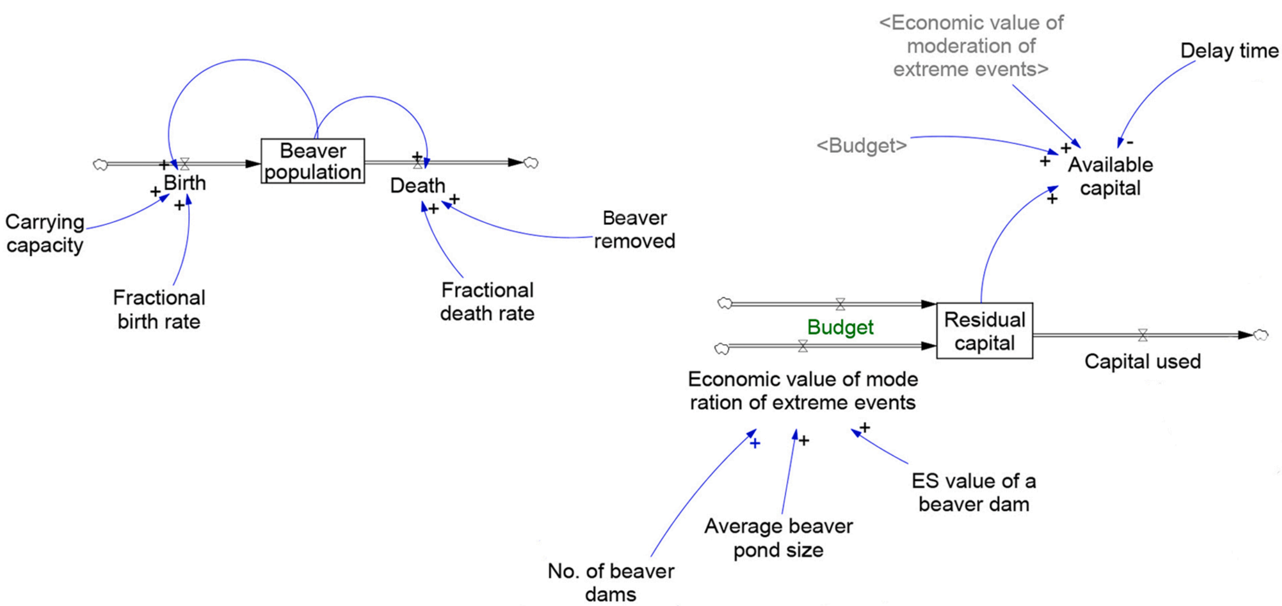

Fig. 4. Stock and flow diagram that defines the dynamics of the variables beaver population (left) and residual capital (right). ES: ecosystem services.

Table 2
Details and sources of the variables kept constant during simulations. Costs were converted assuming an exchange rate of 0.90 € per USD 1.

Variable	*Unit*	*Value*	*Sources of the value*
Beavers per colony	beavers	4	The mean colony size is 4 for Eurasian beavers (Czech and Lisle, 2003; Parker and Rosell, 2001)
No. of people per session	people	12	Set by assuming that in adult learning, small groups (2–12 people) are crucial to open discussion (Brookfield, 1989), which allows adults to better connect new and previous information through their personal experience and knowledge, thereby engaging more in the training material
Proportion of damage compensateion	-	1	Set based on the compensation for beaver management in Switzerland (OFEV, 2016) and for damage by large carnivores in the Piedmont region of Italy (Regione Piemonte, 2024). In both cases, compensation for direct damage is 100% of the commercial value of the damaged property.
Average beaver pond size	km^2	0.02	Usually, 1–2 ha (i.e. 0.01–0.02 km^2) (Thompson et al., 2021)
Average cost of damage per beaver population	€/month	41.66 (i.e. 500 €/year)	Overall, 3.0–4.5% of beaver colonies caused conflict. The cost of damage depended on the land-use category and was highest for forestry. The mean cost of damage caused to forestry per beaver population was 101–1000 €/year (Dutton, 2007).
Proportion of people trained effectively	-	0.5	Set by assuming that information and training sessions were effective for 50% of participants
Cost of one I&T session	€/month	33.33 (i.e. 400 €/year)	Set by estimating the maximum number of information and training (I&T) sessions that can be offered per year given the frequency of other scheduled management practices. Specifically, it assumed that the public administration could hold 10 training sessions of 2 hours each, each involving 2 trainers paid the mean salary of a contract professor in Italy (50 €/h) (total: 2000 €). To this amount were added estimated costs of preparation (1500 €), training materials (500 €), and a room (0 €, assuming that sessions were held in the public administration facilities). Thus, the estimated total cost for 10 training sessions was 4000 €/year (i.e. 400 € per session).
Cost of a pond leveller	€/month	125 € (i.e. 1500 €/year)	The cost of installing, monitoring, and maintaining one pond leveller ranges from USD 1075 (service life of 5 years) (Bruinsma, 2020) to USD 1934 (service life of 7 years) (Hood et al., 2018).
Cost of removing one beaver	€/beavers	135	The mean cost of removing one beaver was ca. USD 150 (i.e. ca. 135 €) (Campbell-Palmer et al., 2015)
Delay time	month	12	Set by assuming that the capital not used in a given year will be available the following year
ES value of a beaver dam	€/km^2*month	933.33 (i.e. 11,200 €/km^2*year)	Thompson et al. (2021) estimated the economic value of the ecosystem service (ES) "moderation of extreme events" assuming that a single beaver dam can modify the volume of flowing water by 3400 m^3/year. The economic gain provided by a beaver dam moderating extreme events equalled USD 124/ha*year (i.e. 11,200 €/km^2*year).
Extension of suitable habitat for beavers	km^2	0.65	Set equal to the minimum extension of suitable habitat for beaver in the Ivrea lakes area (Treves et al., 2022)
Max capital invested for I&T	€/month	333.33	Set by estimating the maximum training that the public administration can perform per year: 10 sessions of 2 hours each with 2 trainers, which would cost 4000 €/year
Minimum Area Requirements	km^2	128.56	The minimum habitat needed to support a beaver population in the Piedmont region (Treves et al., 2022)
Minimum Viable Population	beavers	1143	The minimum population that can persist in the Piedmont region (Treves et al., 2022)
Share of problematic sites	-	0.5	The proportion of sites at which human-beaver conflicts can arise. Set based on land use in the study area, which includes natural zones, such as a European Union Site of Community Importance, and human-made zones. Consequently, an intermediate value was chosen.
Time for social pressure to be effective	months	24	Set by assuming that beaver kits require 2 years to become adults and leave the lodge to establish a new colony (Patenaude, 1984), after which human-beaver

(*continued on next page*)

Table 2 (*continued*)

Variable	*Unit*	*Value*	*Sources of the value*
			conflicts may increase and thus increase the influence of social pressure on performing management practices

values were set based on the literature or their definition. Several variables were kept constant during simulations (Table 2). See Table S1 (Supplementary materials) for the full list of variables.

The resulting SD model (Fig. 5) represents the relationships expressed by the CLD and considers four management practices: pond levellers installation, monetary compensation for damage, beaver removal, and information and training. Pond levellers installation is one of the preventive measures used most to manage conflicts that arise due to flooding caused by beaver dams. Pond levellers regulate the water level in beaver ponds to decrease damage to the surrounding land. Damage compensation provides financial support to landowners impacted by beaver activity. Beaver removal consists of removing beavers, non-lethally or lethally, in problematic areas when their activities cause significant damage.

Information and training includes training sessions to educate local communities about benefits of beavers and preventive measures to promote peaceful coexistence. It also encourages a collaborative approach to wildlife management. Some of the variables that influence these four practices are the *capital required to remove beavers, social pressure*, and *economic value of moderation of extreme events*.

The *capital required to remove beavers* (€/month) equals the *cost of removing one beaver*, i.e. 135 € (Campbell-Palmer et al., 2015), multiplied by the *number of beavers to remove*, which is a function of the *Minimum Viable Population, social pressure*, and the *time needed for social pressure to become effective*.

The *number of beavers to remove* tends to be zero when *social pressure* is zero. *Social pressure* (range -1 to 1) represents the pressure that people exert on management by pushing to remove beavers:

$$\textbf{\textit{Social pressure}} = (\textbf{\textit{Prejudice}} + \textbf{\textit{Peer effects}} - \textbf{\textit{Damage compensation rate}} - \textbf{\textit{Efficacy of I\&T}})/2 \qquad \text{(Eq. 1)}$$

where *prejudice* is the preconceived attitude, *peer effects* is the influence that society has on individual attitudes, *damage compensation rate* is the ratio of the money spent on damage compensation to the mean cost of damage caused by a beaver population, and *efficacy of I&T* is the degree of effectiveness of training, i.e. percentage of participants who experienced a positive change in their attitude as a result of the training sessions.

The *economic value of moderation of extreme events* (i.e. that of the ecosystem service "moderation of extreme events" provided by beavers)

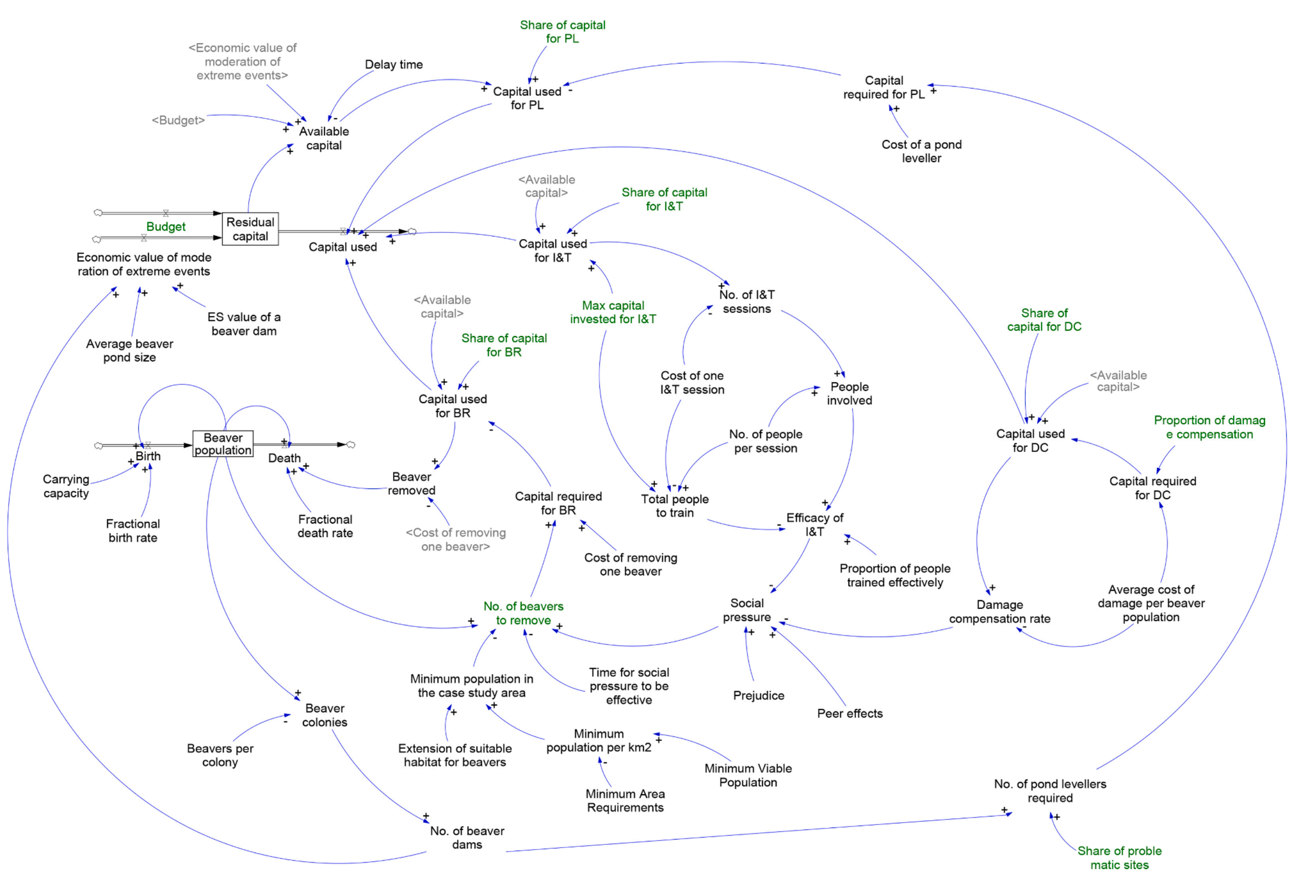

Fig. 5. Systems dynamics model of beaver management. See Table S1 for definitions of all variables (ES: ecosystem services, PL: pond levellers installation, DC: damage compensation, I&T: information and training, BR: beaver removal).

(€/month) was calculated as follows (Thompson et al., 2021):

$$\textbf{Economic value of moderation of extreme events} = \textbf{average beaver pond size} \times \textbf{no. of beaver dams} \times \textbf{ES value} \quad \text{(Eq. 2)}$$

where *ES value* was estimated as 11,200 €/km^2*year (Thompson et al., 2021).

The model assumes that the money saved on flood management due to the economic value of this ecosystem service is reinvested into beaver management. This assumption was made explicitly to explore an integrated approach to resource management, emphasizing how the economic value of ecosystem services could be strategically reinvested to optimize long-term sustainability. It is important to note that this assumption does not reflect existing legal obligations or regulatory frameworks. Instead, it aligns with a policy-oriented perspective often found in sustainable development plans, particularly in European strategies, which encourage reinvestment of resources to amplify ecological and economic benefits. Moreover, this assumption allows the model to simulate a scenario in which reinvestment supports the sustainable management of ecosystem services, providing insights into potential long-term benefits. However, the model remains flexible and can be adapted to simulate alternative scenarios in which savings are allocated differently. The SD model was the starting point for developing the simulation scenarios.

3.2.5. Phases 5 and 6 – model testing and scenario simulation

In phases 5 and 6, the model was tested, scenarios were simulated, and policy-making strategies were identified. The model was tested for robustness under extreme conditions by assessing its behaviour considering minimum and maximum values of the main parameters. To ensure realistic behaviour of the model, we examined how key dynamics responded to extreme parameter variations, verifying that outputs remained plausible and aligned with the underlying system logic. Overall, the model remained consistent even under extreme conditions because the system did not display unrealistic results and remained logically consistent by exhibiting expected feedback loops. After the validation, four scenarios – ecological, social, economic, and policy making – were simulated for 240 months by varying specific model variables (Table 3).

3.2.5.1. Ecological scenario. The ecological scenario was related to population dynamics (i.e. births, deaths, and available resources). It assessed the system's response by allowing the beaver population to grow when allocating the budget equally to the four practices. It was simulated by varying the *carrying capacity* (i.e. number of individuals that the environment can support) and *fractional birth rate* (i.e. births per year per breeding pair). *Carrying capacity was* varied from 20 (i.e. the extended suitable area 2.2 km^2) to 50 to 100 (set by assuming that beaver spread and adapt to the surrounding environment), and *fractional birth rate* was varied from 0 to 0.06 to 0.10/month (Bergerud and Miller, 1977), based on an observed birth rate of 2–4 kits per year per pair (Bergerud and Miller, 1977; Shirley et al., 2015).

3.2.5.2. Social scenario. The social scenario was related to the community perception of and attitudes towards beaver presence and the management of human-beaver interactions. This scenario assessed the system's response when the local community was favourable (or not) to the presence of beaver. It was simulated by varying the social variables *peer effects* and *prejudice* to the same value regardless of the management policy, which was kept equal to that in the ecological scenario. *Peer effects* was varied from 0 (i.e. no influence) to 1 (i.e. maximum influence), and *prejudice* was varied from 0 (i.e. no prejudice) to 1 (i.e. maximum prejudice), together in steps of 0.25.

3.2.5.3. Economic scenario. The economic scenario was related to management costs and the value of ecosystem services that beavers provided. This scenario assessed the system's response to investing a certain budget for beaver management (or not) and to considering ecosystem services (or not). It was simulated by varying *budget* (i.e. the money the public administration allocates for beaver management) and *ES value of a beaver dam* (i.e. the monetary value of the ecosystem service "moderation of extreme events" provided by a beaver dam). *Budget* was varied from 0 to 1000 € to 5000 € to 10,000 €/year (i.e. 0, 83.33, 416.66, and 833.33 €/month, respectively), and *ES value of a beaver dam* was set to either 0 € (i.e. ecosystem services not considered) or 933.33 €/km^2*month (based on estimates of Thompson et al. (2021) that the economic gain provided by a beaver-created wetland that moderated extreme events was USD 124/ha*year which equals 11200 €/km^2*year).

3.2.5.4. Policy-making scenario. The policy-making scenario was related to the relative capital invested in the four management practices and the priority with which they were implemented. This scenario assessed the system's response to three policy sub-scenarios simulated by modifying the share *of capital*: (1) 0.25 for each of the four practices, (2) 1.00 for one practice at a time, or (3) giving priority to practices that enhance human-wildlife relationships (Lute and Gore, 2014; Mathevet et al., 2018). The priority order followed a pro-prevention approach, i.e. (i) pond levellers installation, (ii) damage compensation, (iii)

Table 3
Values used for the main variables in scenario simulations. (ES: ecosystem services, PL: pond levellers installation, DC: damage compensation, I&T: information and training, BR: beaver removal).

Variable	Unit	Scenario (n = number of simulations)					
		Ecological (n = 9)	*Social (n = 5)*	*Economic (n = 7)*	*Policy making*		
					1 (n = 1)	*2 (n = 4)*	*3 (n = 3)*
Carrying capacity	beavers	20, 50, 100	50	50	50	50	50
Fractional birth rate	1/month	0, 0.06, 0.10	0.06	0.06	0.06	0.06	0.06
Peer effects	-	0.50	0, 0.25, 0.50, 0.75, 1	0.50	0.50	0.50	0.50
Prejudice	-	0.50	0, 0.25, 0.50, 0.75, 1	0.50	0.50	0.50	0.50
Budget	€/month	83.33	83.33	0, 83.33, 416.66, 833.33	83.33	83.33	83.33, 416.66, 833.33
ES value of a beaver dam	€/month	933.33	933.33	0, 933.33	933.33	933.33	933.33
Share of capital	-	0.25 for each practice	0.25 for each practice	0.25 for each practice	0.25 for each practice	1.00 for one practice at a time	Capital allocated first to highest-priority practice (i.e. PL) and progressing to the others (i.e. DC, I&T, and BR)

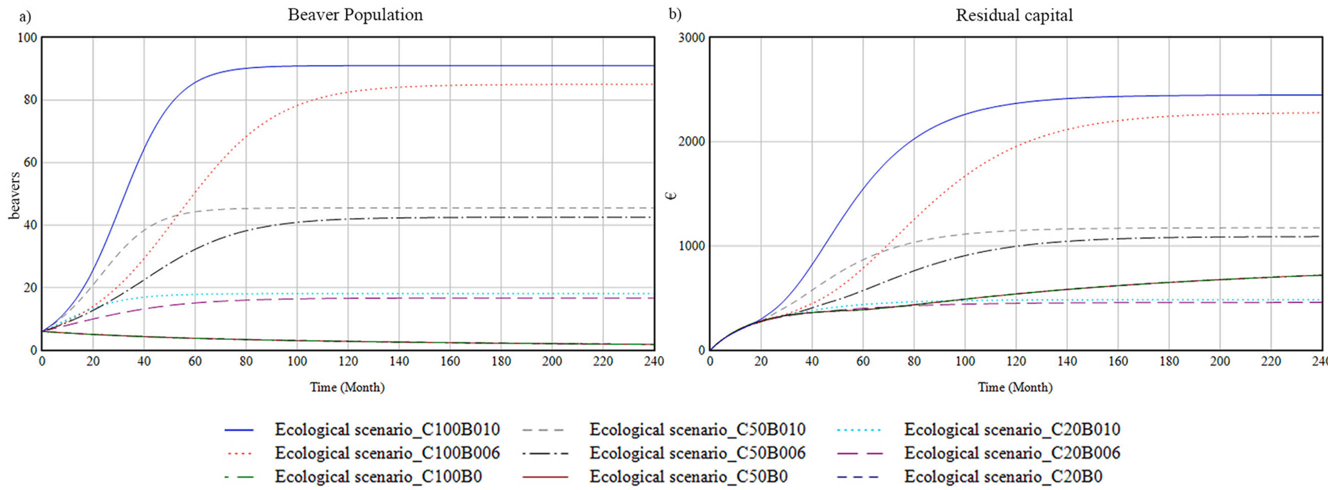

Fig. 6. Dynamics of the (a) beaver population and (b) residual capital in the nine simulations of the ecological scenario as a function of the carrying capacity (after C in the legend) and fractional birth rate (per month per breeding pair, after B in the legend).

information and training, and (iv) beaver removal, by implementing sequentially the four practices based on the available budget, with capital allocated to the highest-priority practices first. This approach simulated how budget limitations influence the feasibility and extent of implementing management strategies. In this sub-scenario, the *budget* invested in management also varied (i.e. 83.33, 416.66, 833.33 €/month) along with the capital.

4. Results and discussion

The previous section outlines the development of the system dynamics model to support human-beaver management and related-policy design. This section presents the results and discussion of the scenarios simulations (i.e. ecological, social, economic, and policy-making scenario). The results are illustrated by the dynamics predicted for the beaver population and residual capital for the four scenarios.

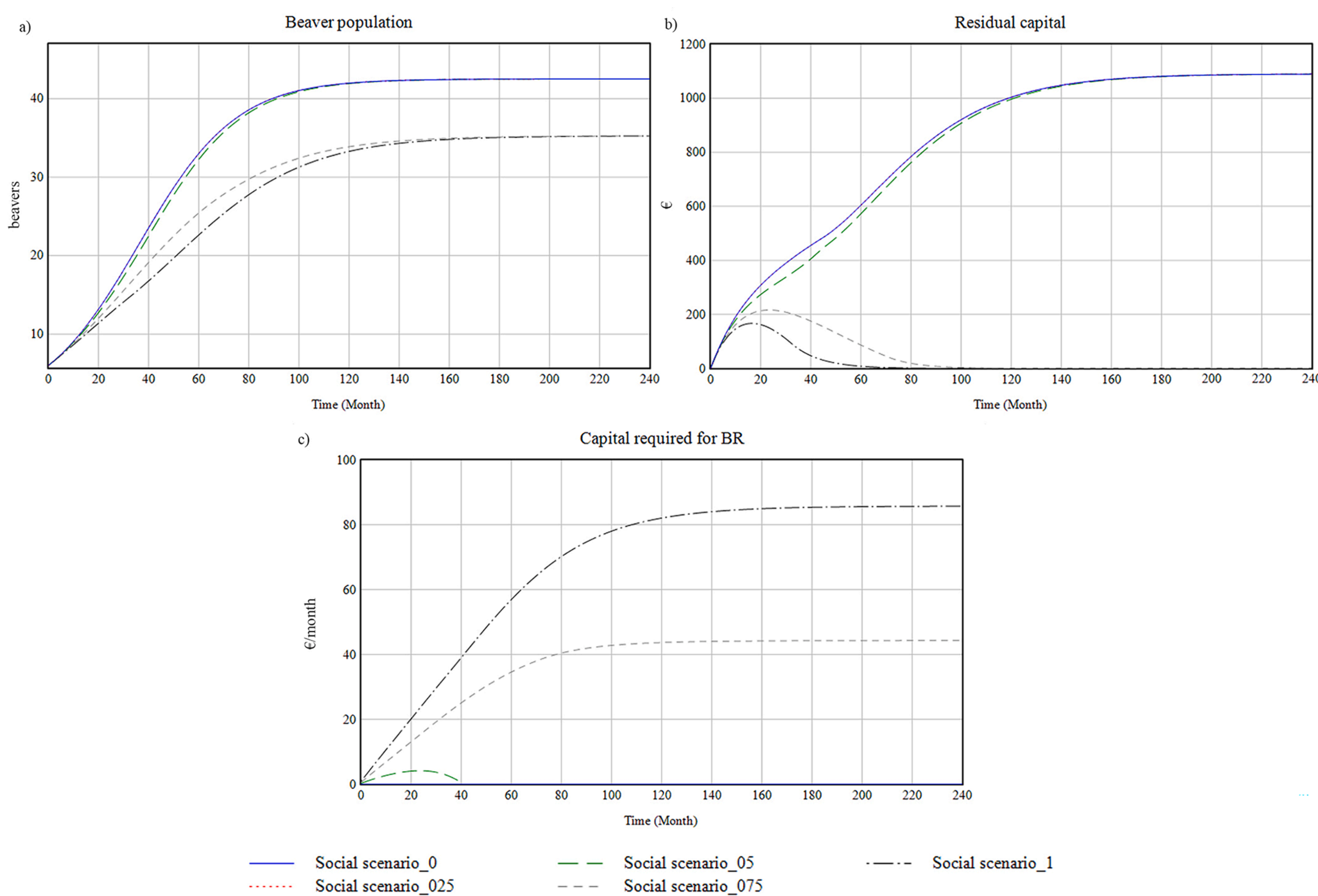

Fig. 7. Dynamics of the (a) beaver population, (b) residual capital, and (b) capital required for beaver removal (BR) in the five simulations of the social scenario as a function of prejudice and peer effects, both set equal to 0, 0.25, 0.5, 0.75 or 1.

4.1. Ecological scenario

In the ecological scenario, when *fractional birth rate* > 0, the simulated population increased logistically and quickly stabilised regardless of *carrying capacity*, as designed (Fig. 6a). The population nearly reached *carrying capacity* most quickly when the *fractional birth rate* was 0.10/month. When *fractional birth rate* $= 0$, the population decreased to slightly less than the initial population size of 6 beavers and remained stable. The population never exceeded the *carrying capacity*.

The population trend influenced *residual capital* (Fig. 6b). When the population decreased, *residual capital* increased to a constant value because less capital was used for practices; in addition, less ecosystem services were provided. When the population increased, *residual capital* increased and was largest when the population reached a *carrying capacity* of 100. Although a large beaver population required investing a large amount of capital to manage it, this result was not surprising as the increasing population also increased the value of the ecosystem services contributed to *residual capital*. In contrast, *residual capital* was smallest when *carrying capacity* $= 20$.

4.2. Social scenario

In the social scenario simulations, the population tended to increase logistically (Fig. 7a). When *social pressure* was negative (i.e. *prejudice* and *peer effects* ≤ 0.25), which represented when people welcomed beavers, no beavers were removed, and the population increased nearly to the *carrying capacity* of 50. In contrast, as *social pressure* increased, the maximum beaver population decreased (e.g. when *prejudice* and *peer effects* > 0.50, the population stabilised at ca. 48 beavers).

As social pressure increased, it indirectly decreased *residual capital* by decreasing the economic value of the ecosystem service (Fig. 7b). Thus, when *prejudice* and *peer effects* $= 1.0$, *residual capital* decreased until nearly the entire *budget* and contribution of the economic value of the ecosystem service was spent on management. The model also predicted that the amount of capital required each month to remove beavers did eventually stabilise (Fig. 7c), which is important for policy makers to understand the amount of capital required to meet social demands. In contrast, when *social pressure* was lower, no money was spent to remove beavers, and the public administration *budget* could be used to implement the other three practices.

4.3. Economic scenario

In the economic scenario simulations, the population increased logistically to a maximum that decreased as the *budget* increased (Fig. 8a). When the *budget* $= 0$ €/month, the population increased nearly to the carrying capacity. As the budget increased, the threshold to which the population tended decreases but when *budget* ≥ 416.66 €/month, the population increased in the same way as that for growth without beaver removal. The change in the *budget* thus influenced *residual capital* and how it was spent on management (Fig. 8b). *Residual capital* increased to nearly an asymptote when *budget* $= 83.33$ € or 416.66 €/month or linearly when *budget* $= 833.33$ €/month, whether the economic value of the ecosystem service was considered or not. When *budget* ≤ 416.66 €/month, beaver removal increased (Fig. 8c), and thus the economic value of the ecosystem service decreased. In addition, as the *budget* increased, *residual capital* also logically increased. Thus, when a certain *budget* was reached, less money was needed for management.

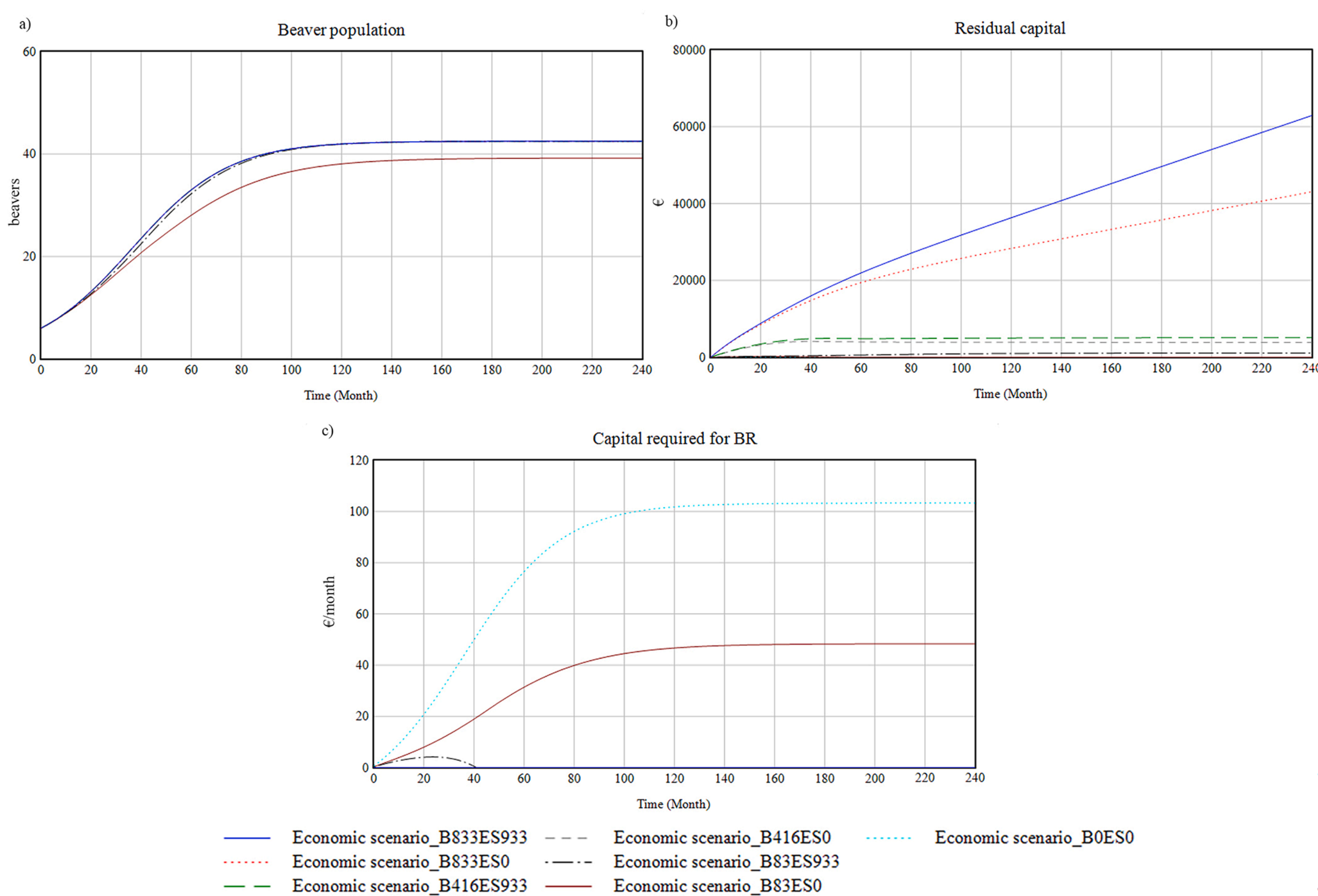

Fig. 8. Dynamics of the (a) beaver population, (b) residual capital, and (c) capital required to for beaver removal (BR) in the seven simulations of the economic scenario as a function of the budget (€/month, after "B" in the legend) and the economic value of the ecosystem service (€/month, after "ES" in the legend).

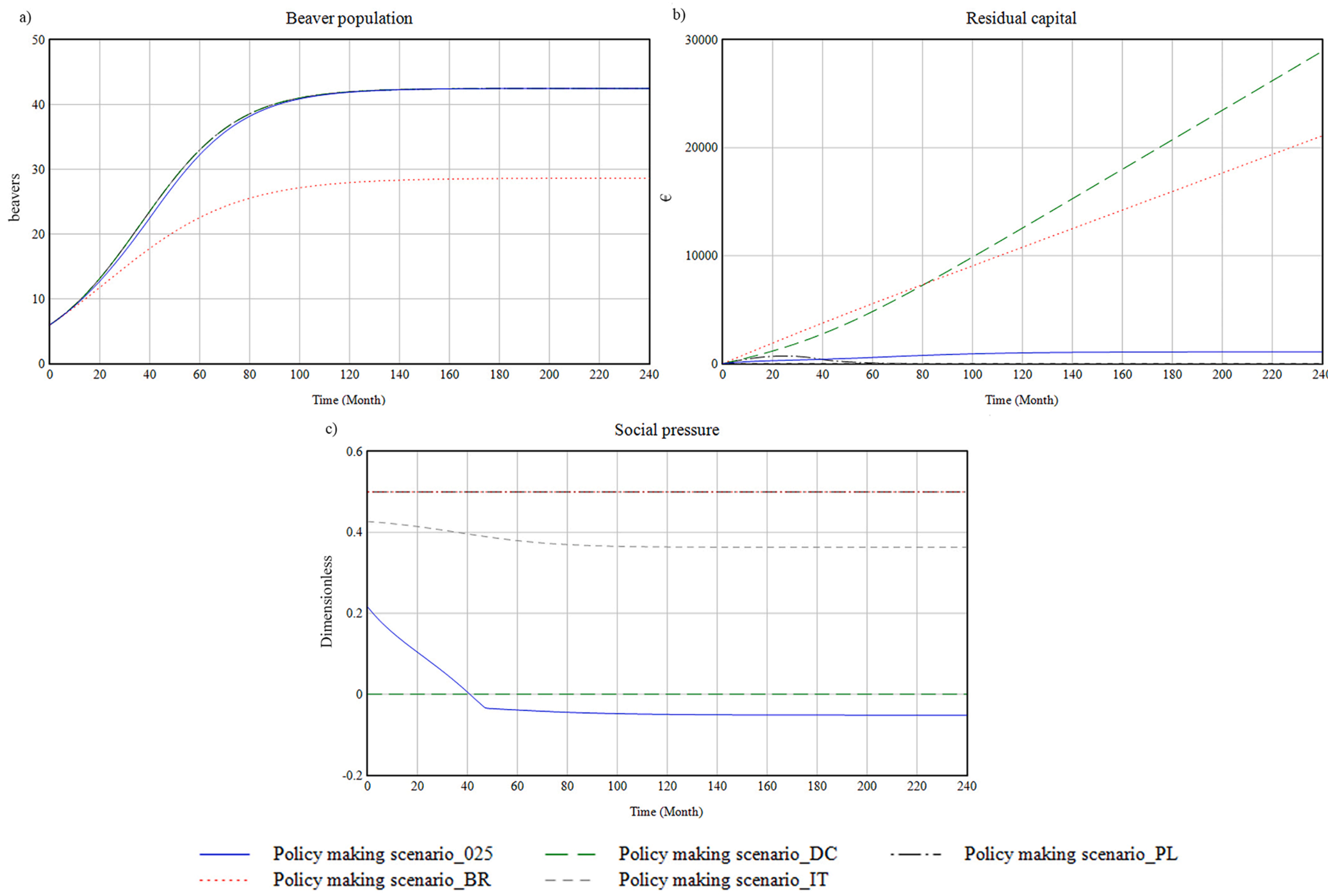

Fig. 9. Dynamics of the (a) beaver population, (b) residual capital, and (c) social pressure in the five simulations of the first two policy-making sub-scenarios: dividing the capital among all four practices ("025″ in the legend) or implementing one practice at a time (beaver removal ("BR"), damage compensation ("DC"), information and training ("IT"), or pond levellers installation ("PL")).

4.4. Policy-making scenarios

In the first two policy-making sub-scenarios, the population nearly reached the *carrying capacity* except when only beaver removal was implemented (Fig. 9a). The beaver removal decreased the maximum population size and thus the economic value of the ecosystem service. Thus, if beavers are not removed, the conditions are even more favourable for natural population growth. *Residual capital* increased the most in the simulation with only damage compensation, which suggests that it was used efficiently, followed by the simulation with only beaver removal. In the simulations with only installation of pond levellers or information and training, *residual capital* increased only slightly, and only at the beginning of the simulation. In contrast, the sub-scenario that divided capital equally among the four practices had intermediate values of *residual capital*. In addition, *social pressure* was highest when only removing beavers or installing pond levellers and lowest when only compensating for damage. Only compensating for damage decreased conflict without decreasing the beaver population or *residual capital*. Only providing information and training decreased *social pressure* only moderately, which suggested that training sessions are not sufficient to decrease it completely, although they increased awareness of beavers and changed community attitudes. Therefore, when several strategies are combined, social pressure can decrease until it reverses (i.e. becomes favourable to beavers). Individual policies such as removing beavers or performing preventive measures such as installing pond levellers did not seem to decrease social pressure: beavers continued to be perceived negatively despite the decrease in their damage.

In the third policy-making sub-scenario, the simulated prioritising of

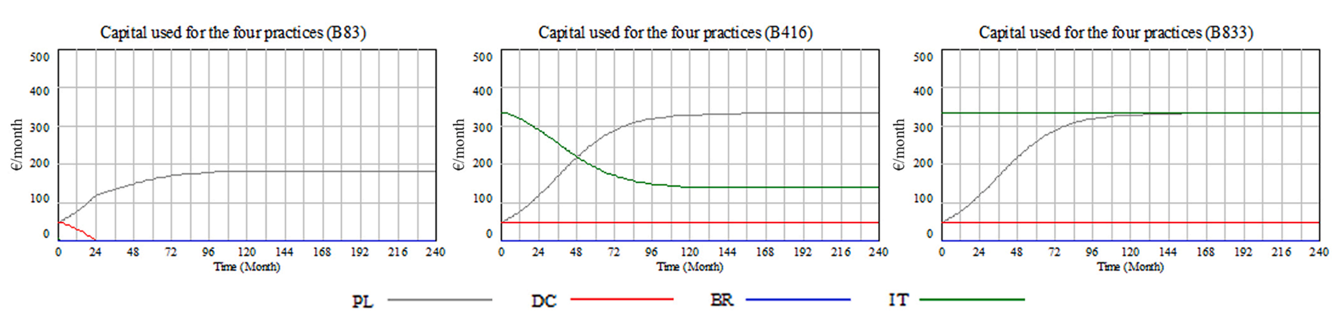

Fig. 10. Dynamics of the beaver population, residual capital, and social pressure in the third policy-making sub-scenario as a function of the budget (€/month, after "B" in the legend). PL: pond levellers installation, DC: damage compensation, BR: beaver removal, and IT: information and training.

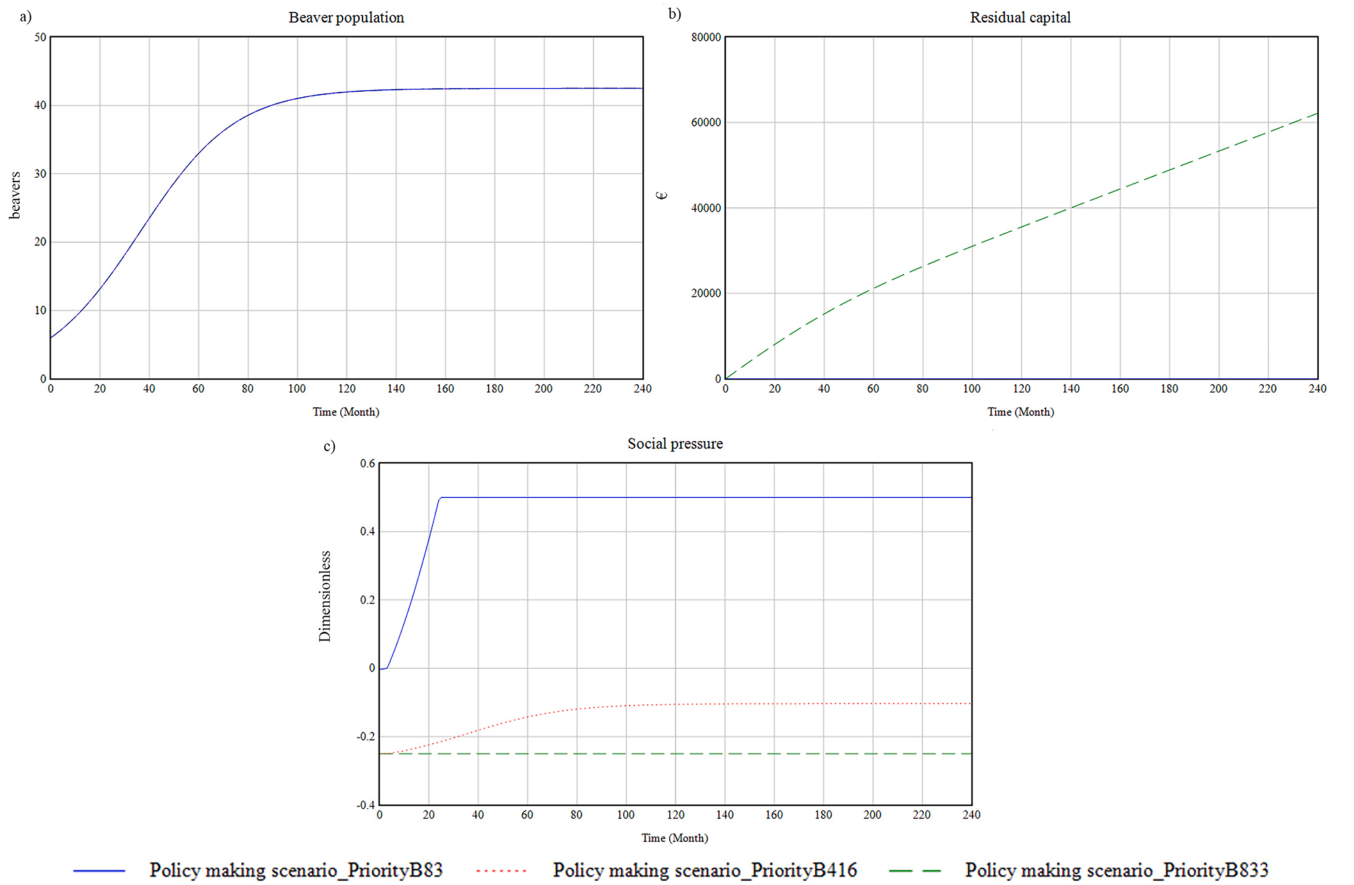

Fig. 11. Dynamics of the capital used for the four management practices in the third policy-making sub-scenario as a function of the budget (€/month, after "B" in the title).

the four practices did not seem to influence the beaver population, which increased logistically regardless of the *budget* (Fig. 10). This was likely because beavers were never removed due to a lack of *budget* or to a decrease in *social pressure* as a consequence of the other practices. Indeed, compensating for damage or providing information and training decreased *social pressure* until it reversed. The change in the *budget* and how it was spent on management influenced *residual capital*, which increased little or not at all when *budget* = 83.33 € or 416.66 €/month, or nearly linearly when *budget* = 833.33 €/month. Thus, like for the economic scenario, when a certain *budget* was reached, less money was needed for management. The budget was allocated first to highest-priority practice (i.e. pond levellers installation) and progressing to the others (i.e. damage compensation, information and training, and beaver removal) (Fig. 11). When *budget* = 83.33 €/month, the practices implemented were pond levellers installation and damage compensation for nearly a year. When budget = 416.66 €/month, the practices implemented were pond levellers installation, damage compensation, and information and training. When budget = 833.33 €/month, all the practices were implemented completely except for beaver removal.

The SD model clearly mapped and described the complexity of human-beaver management. It predicts how a beaver population can rapidly reach an equilibrium based on the local carrying capacity and birth rates, which highlights the importance of proper habitat management and conditions favourable for beaver conservation (OFEV, 2016; Serva et al., 2023). In addition, the predicted *residual capital* indicated that a larger beaver population can generate more ecosystem services, while potentially requiring an increase in capital investment depending on the efficiency of management practices (Brazier et al., 2021; Thompson et al., 2021).

In the social scenario, *social pressure* influenced management decisions greatly. The degree of social acceptance of beavers influences the stability of a beaver population, beaver removal, and, consequently, the availability of capital. Thus, management of social perceptions could be a crucial element in management strategies, suggesting that education, awareness campaigns, and public engagement may help reduce conflict and promote positive ecological outcomes (Auster et al., 2023; Hohm et al., 2024).

In the economic scenario, the relationship between the beaver population and budget invested was not surprising; however, the model predicted investment thresholds beyond which the effectiveness of management changed positively, which decreased the need for further investment. This implies the need to plan the budget appropriately to optimise economic and ecological results.

In the policy-making scenarios, implementing the different management practices had variable effects on the beaver population and *residual capital*. The beaver removal decreased the population and thus the economic value of the ecosystem service, suggesting that applying a well-balanced combination of management practices is essential. Moreover, compensating for damage increased *residual capital* the most, suggesting that it may be more effective in case of conflicts than the other practices to reduce social pressure. However, to be more effective, damage compensation should be part of a comprehensive approach that includes setting up proactive measures to prevent conflicts in the first place (Nyhus et al., 2005; Ravenelle and Nyhus, 2017).

These findings are further highlighted by the prioritisation of the four management practices as (1) pond levellers, (2) damage compensation, (3) information and training, and (4) beaver removal, which emphasises out the importance of prevention and ensures conservation management of the species while respecting the interests of local communities. If implemented correctly, these practices can help not only mitigate damage, but also decrease the cost of management, while improving community attitudes towards beavers.

5. Conclusions and future perspectives

The SD model provides a holistic view of the key dynamics of human-beaver interactions by (1) considering conflicts and benefits associated with beaver presence and (2) simulating scenarios that consider ecological, social, and economic dimensions. Considering conflicts and benefits recognises the intrinsic value of species in the system and highlights the importance of considering not only the direct impacts of wildlife but also their broader ecological contributions, in line with current species-management policies. Considering ecological, social, and economic dimensions facilitates assessment of management strategies that support decision-making. Indeed, effects of management practices predicted by SD models can be used in several ways. First, they are a useful tool for policy makers to visualise cause-effect relationships and assess impacts of their choices on the socio-ecological system. Second, they can be used as a discussion tool to involve stakeholders in a participatory management process in which the model helps stakeholders understand the complexity of the system, provides information about positive and negative beaver impacts, and addresses human-beaver coexistence.

To increase understanding of the multiple facets of human-beaver management, future studies could expand the present study by exploring other conflicts and/or ecosystem services. Future studies could also assess multiple conflicts and benefits at the same time to assess potentially overlapping effects, or instead apply the model to different geographic or socio-economic contexts by changing scenario parameters.

In conclusion, the relationships among beaver behaviour, ecological processes, and human activities create a system of feedback loops, nonlinear dynamics, and emergent properties that require adaptive and flexible management strategies. By viewing beaver management through the lens of complex systems, the need for human-beaver management that does not stop at conflict management but values the interconnection of ecological and human components becomes crucial.

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CRediT authorship contribution statement

Anna Treves: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giovanni Zenezini:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Elena Comino:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2025.111057.

Data availability

Data will be made available on request.

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