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Research article

A picit jeu: Agent-based modelling with serious gaming for a fire-resilient landscape

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ABSTRACT

Wildfire governance requires addressing driving physical, biological and socio-economic processes, by promoting the development of fire-resistant and resilient landscapes. These landscapes can best be achieved by strategies that integrate fuel management for direct prevention with allied socio-economic activities, through the collaboration of stakeholders with different and sometimes conflicting interests. This work aims to address the need for new approaches supporting the participatory process of collective decision-making, helping stakeholders explore land management strategies for landscape fire resilience. We present and discuss a methodology combining agent-based modelling with a role-playing game. It was tested in a valley of the Italian Alps, involving 23 local stakeholders in forest and pasture management in three game sessions. Evaluation was based on observation of game sessions, collection of feedback via immediate post-session debriefing and questionnaires, and long-term (multi-year) assessment carried out through semi-structured interviews. We found the methodology valuable for facilitating discussion among different stakeholders, who were able to identify context-related challenges (land fragmentation and land abandonment, stakeholders' limited collaboration, controversial drives of European funding) and possible strategies for producing a fire-resilient landscape (community management forms of pastoralists activities for maintaining land cover diversity). The approach also triggered a positive process for longer-term change. By analysing the outcomes, we are able to identify four key recommendations for future work using serious gaming for sustainable landscapes: 1) aim for an even composition of session groups, 2) consider the multiple levels of organisation in the area, 3) use the allocation of game roles to disrupt power dynamics, and 4) seek to involve the broadest stakeholder spectrum in developing the game itself.

1. Introduction

Wildfires have severe impacts on ecosystem services and human health worldwide, including casualties, negative consequences on air quality and effects on the global carbon budget (Bacciu et al., 2022). The annual cost of wildfires in the United States alone is estimated at between $71.1 billion and $347.8 billion (UNEP, 2022), while in 2023 wildfires affected an area of more than 500,000 ha in the European Union countries, causing severe damage to the environment and producing around 20 megatonnes of CO2 emissions (San-Miguel-Ayanz et al., 2024).

Wildfire governance in a context of global change requires a strategy addressing the physical, biological, and socio-economic processes that drive the phenomenon in a landscape (Bowman et al., 2013; Bacciu et al., 2022; Kirschner et al., 2023). In Europe, land governance actions aim to manage some critical causes of wildfire impacts (e.g., landscape flammability, rural land abandonment, illegal fire uses, lack of community-based fire adaptation) by promoting the development of fire-resilient landscapes (Moreira et al., 2020). This means territories where governance actions exert leverage on the wildfire regime so that

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its effects are compatible with the delivery over time of key ecosystem services (e.g., water supply, primary productivity, biodiversity) and with the socio-economic system in the area (e.g. agroforestry productions, tourism, energy industry) (Fernandes, 2013; Thacker et al., 2023).

Consequently, in many European territories, wildfire governance programs are in place that integrate strategic fuel management planning for direct prevention (e.g., strategic fuel breaks supporting active firefighting) with the planning of socio-economic activities that have an indirect fire regulatory effect by creating a mosaic less prone to fire in synergy with direct prevention, such as agro-silvo-pastoral value-chains, biodiversity conservation or energy supply (Tedim et al., 2016; Pais et al., 2020; Spadoni et al., 2023; Pulido et al., 2023).

However, the possibility of creating sustainable processes to achieve fire-resilient landscapes requires collaboration among multiple stakeholders (e.g., forest managers, private owners, nature conservation agencies, and enterprises in the agro-pastoral, food, energy, or tourism sectors) with interests in the territory that often appear challenging to synergize or even conflict (Canadas et al., 2016). Developing a common, shared strategy to promote integrated planning processes for fire-resilient landscapes requires participatory decision-making that facilitates adaptive learning, understanding the interests at stake, and collaboratively defining win-win strategies that activate sustainable processes over time (Otero et al., 2018; Ascoli et al., 2023).

The use of games in natural resources management has increasingly received attention in recent years for conflict mediation, social learning and collective decision-making (Madani et al., 2017; Wesselow and Stoll-Kleemann, 2018; Flood et al., 2018; Rodela et al., 2019). Companion Modelling (ComMod) emerged as a gaming approach, relying on "the synergistic effects between role-playing games (RPG) and agent-based models (ABM) to facilitate information sharing, collective learning and exchange of perceptions on a given concrete issue among researchers and other stakeholders" (Ruankaew et al., 2010). On the one hand, agent-based modelling (ABM) is a well-known methodology for analysing the interactions between people, things, places and time. ABM is often used in socio-ecological system studies to integrate human behaviour models with ecological models (Kline et al., 2017) and a variety of applications in wildfire research exists in the literature (Millington et al., 2008; Charnley et al., 2017; Spies et al., 2017; Ribeiro et al., 2023). On the other hand, serious games are an innovative participatory approach to exploring, learning about, and discussing the complexity of the socio-ecological system, especially when many conflicting interests exist in it (Speelman et al., 2018). Games can support collective negotiations and help define common strategies toward a collectively recognised problem, putting into play the participants' perception of the problem and their experience.

Examples of serious games dealing with wildfire risk exist in the literature, focusing on different aspects of risk management, such as firefighting training simulation (Backlund et al., 2007; Caroca et al., 2019), emergency decision-making (Ji et al., 2024), disaster preparedness (Johns et al., 2024) and social awareness (Pereira et al., 2014). However, they were developed to strengthen risk preparedness and response, while, to our knowledge, a serious game focusing on building fire-resilient landscapes involving both direct and indirect fire regulatory processes has not been developed yet. Moreover, none of the cited works successfully represent the interaction between the diverse perspectives and priorities of local stakeholders. Representing and putting them into play is crucial for supporting a participatory process where indeed those interactions must be taken in consideration, discussed and leveraged for developing successful wildfire impacts mitigation strategies.

This work aims to address the need for collaborative decision-making to develop integrated planning processes for fire-resilient landscapes by presenting and assessing an innovative participatory approach based on ComMod principles, focused on exploring land management strategies for landscape fire resilience. We tested the methodology in a study area located in the Italian Alps, by (1) developing an ABM representing the effect of forest and pasture management actions on wildfire risk in Valchiusella, (2) creating the game *A Picit Jeu*[1] using the model for exploring the results of different strategies, and (3) using *A Picit Jeu* for involving local stakeholders in collective discussions on land management scenarios for fire prevention.

This work also intends to contribute to the research gap in impact assessment of games used in natural resource management (which has largely been absent or only short-term focused; Calderón and Ruiz, 2015; Rodela and Speelman, 2023) by presenting a multiple-time-frame evaluation of the impact of the game experience. A short-term assessment was supported by the observation and recording of the game sessions, and by participants' feedback via end-of-session debriefings and questionnaires. A long-term evaluation was carried out two years later by interviewed participants to explore what influence the game subsequently had on land management decision-making and the network of stakeholders concerned. We describe the results of such a multiple-time-frame impact assessment, while discussing its advantages and limits.

The following section presents the study area and describes in detail the procedure adopted. We then introduce and discuss the results of the game development process, of the game sessions and of the evaluation steps. In the Conclusion section, we consider what lessons can be learned to apply in other landscapes and contexts.

2. Materials and methods

2.1. Study area

The study area is Valchiusella, an Alpine valley of about 143 km^2 in the northwestern part of Italy, in the Piemonte region (Fig. 1).

The valley's altitude ranges between approximately 400 m and 2800 m for the highest peaks. The surface is divided into eight municipalities, with a total resident population of 5161 inhabitants on January 1, 2023 (data available at https://dati.istat.it). The population has gone through a process of depopulation typical of Alpine valleys since the end of the 19th century, which was characterised by the abandonment of traditional farming activities (MacDonald et al., 2000). This process has also caused the still ongoing expansion of pioneer vegetation – tall grasses, shrubs, and trees – on abandoned pastures, with tangible effects on fire hazard (Ascoli et al., 2020, 2021). The local fire regime is characterised by a predominance of fires during winter and close to it (see data available at https://www.geoportale.piemonte.it/geocatalogorp). In this season the fully cured vegetation, lower rainfall frequency, and warm, dry foehn winds increase the probability of accidental ignitions producing extensive fires (Valese et al., 2014), such as the one occurred in April 2022 in the municipality of Rueglio, which involved around 300 ha of pastures and forests and caused severe damages to some buildings (local forest technicians, personal communication).

Valchiusella forestry area, which covers around 43% of the total surface, is shared between private owners and municipalities. A prominent role in forest management is played by the Consorzio Forestale del Canavese (CFC). The CFC was born in 2002 as a unitary management body for a non-administrative region including Valchiusella, with the aim to support the sustainable management of forests from a multifunctional perspective and through long-term planning. The CFC manages 1977 ha of forest surface in the valley (32% of the total forest surface) almost entirely belonging to seven out of eight municipalities (CFC forest technicians, personal communication).

Most of the alpine pasture areas of the valley are owned by the

[1] The game's name "A Picit Jeu" is a word pun in the local dialect of Valchiusella, meaning "a small game" but sounding also close to "A Picit Feu", which literally means "over small fire" and refers to a phenomenon evolving slowly.

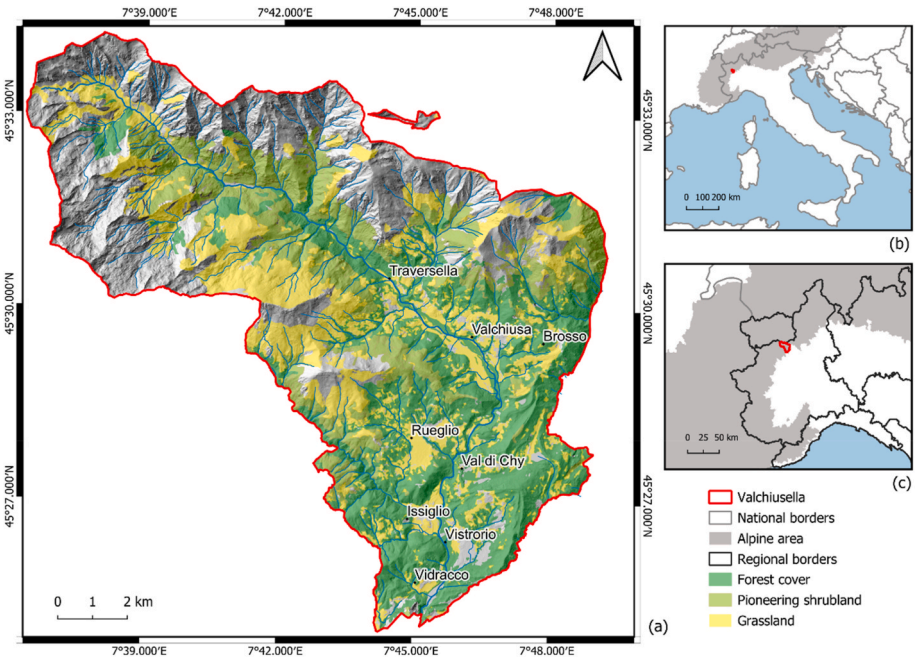

Fig. 1. Map of the study area. In (a) the extent of the forest cover, pioneering shrublands and grasslands is shown. The forest cover and pioneering shrubland layer are taken from the regional forest map (last update in 2016, https://www.geoportale.piemonte.it), while the grassland cover is derived by subtracting those from the "Grasslands, meadow pastures, bushes" layer (derived by elaboration of the IPLA Land Cover 2003 and available at https://geoportale.igr.piemonte.it). The layer does not include rupicolous grasslands. (b) and (c) place the study area at a national and regional level, respectively.

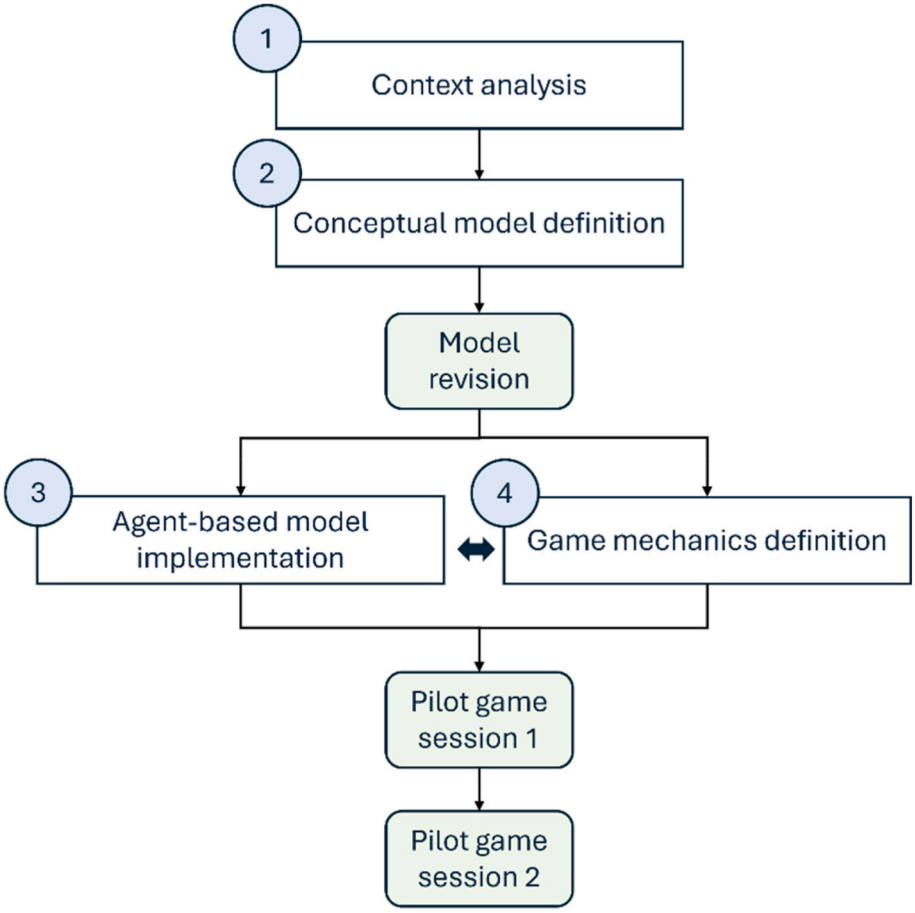

Fig. 2. Diagram of the four-phase methodology adopted for the game design. The three review steps are represented in green boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

municipalities. Farmers typically rent those lands with multiannual contracts and bring their animals to graze in summer. Usually, a nearby municipal alpine hut is rented together as a shelter for animals and a temporary residence for farmers.

The existence of a variety of public and private stakeholders of forest and pasture management, together with the challenges caused by the rural abandonment process to fire prevention, makes Valchiusella an excellent case study for the purposes of this work.

2.2. The game design

The design of *A Picit Jeu* was based on four phases (Fig. 2):

1. analysis of the local context through semi-structured interviews;
2. definition of the conceptual model of the local socio-ecological system (SES);
3. implementation of the agent-based model;
4. definition of the role-playing game mechanics.

Phases 3 and 4 were carried out at the same time and implied a continuous interaction with each other.

Three review steps were taken at different moments of the game design process. The aim was to verify the appropriateness of the representation of the socio-economic and ecological dynamics of the study area context, as well as the playability of the game. They involved local technicians of the CFC and researchers in the domain of geography, land management, and wildfires.

2.2.1. Context analysis

The methodology proposed in this work for the game design aims at tailoring the game dynamics to the specific context it is conceived for. The analysis of the context was conducted through semi-structured interviews with local stakeholders, focused on the interactions between human and ecosystem dynamics in the framework of wildfire risk.

Twenty-five interviews were carried out, involving 27 interviewees. The interviewees were identified among five categories of stakeholders involved in local land management, forest management and wildfire issues:

- Mayors or municipal administrators in charge of land management tasks – contacts were provided by the CFC.
- Forest firefighter volunteers – priority was given to the firemen of each local volunteer firefighter team. Four valley municipalities had their own team at the moment of the interviews: Val di Chy, Rueglio, Traversella and Vidracco. The head of the Valchiusella section was also interviewed.
- Forest workers – the owners of the forestry companies registered in the official provincial list were interviewed. Other respondents were contacted thanks to the indications provided by the CFC. In addition, members of a land consortium existing in the northern part of the valley were interviewed.
- Members of local environmental associations – selected on the recommendation of association leaders.
- Farmers – respondents were first identified among the members of a local association of producers for the promotion of local cheese. Other interviewees were suggested by the already involved farmers ('snowballing').

The interview canvas was made of 20 questions focused on the personal relationship with the local community, the experience with forest management, the role of wildfires in the ecosystem and the existing fire prevention strategies, the local forest management status and actors, and the value of ecosystem services. The interviews were carried out over around two months, so it is possible that some early participants had the opportunity to exchange ideas about the questions' content with later participants before their interviews. However, this is not a limitation for our work given that the purpose of this activity was to get an overview of the interactions between human and ecosystem dynamics and of the local challenges related to wildfire risk, instead of a precise personal point of view. Moreover, any exchange of ideas between stakeholders already happening at this time was perfectly in line with the general aim of this work of fostering collaborative decision-making.

Interviewees' answers were analysed through thematic analysis (Braun and Clarke, 2006) to identify the recurrent topics and mapped into thematic areas. For each of the seven thematic areas mapped, a specific issue directly or indirectly related to wildfire prevention in the valley was formulated, based on the respondents' contribution. Finally, each issue was translated into a precise purpose to be integrated into the game's design, such as a specific topic on which the game should trigger discussion or concerning which it should help a learning process.

2.2.2. Conceptual model definition

For designing game mechanics representative of the real-world situation, a conceptual model of local Social Ecological System fire prevention issues was defined. A procedure adapted from the ARDI method proposed by Étienne and colleagues (Etienne, 2009; Etienne et al., 2011) was used. The ARDI method was conceived in the framework of the ComMod approach for building a shared description of the SES among the stakeholders involved in the process, representing its elements by means of diagrams. In this work, the four ARDI elements and steps (Actors, Resources, Dynamics and Interactions) were used by the authors as a guideline to formalize the insights collected through the interviews into an SES conceptual model serving the design of the game mechanics.

2.2.3. Agent-based model implementation

The SES conceptual model was then transformed into an agent-based model (ABM) in NetLogo. The NetLogo language was chosen because of its free access, wide diffusion in environmental studies, ease of learning, and good user support (Kravari and Bassiliades, 2015; Wilensky and Rand, 2015). The interface tab of the model was designed to be used as the 'board' of the game by projecting it on a screen clearly visible to all the players. The model was created with a series of commands the game master can enter during the simulation depending on players' decisions about forest and pasture management actions. The game was intended to reproduce a primary general pattern: the less players undertake landscape management actions (e.g., by thinning and cutting forests or grazing pastures), the higher the probability that a fire will burn a large land area. The detailed description of the model following the ODD standard protocol for ABMs (Grimm et al., 2006) and the model code itself are published in (and downloadable from) the COMSES library (Vigna and Millington, 2024).

2.2.4. Game mechanics definition

While coding the ABM, the game mechanics were also defined. This step was based on a translation process of the actors, resources, dynamics and interactions of the SES conceptual model into game roles and mechanics, such as players' actions on the board, players' interactions, game materials and spatial and temporal settings. Since this step was strictly dependent on the previous step and *vice versa*, a continuous interaction between the two was necessary to shape the game mechanics to the model's possibilities and to adapt the model to the needs of the gameplay.

2.2.5. Review steps

The first review step was carried out after the conceptual model definition phase. The main aim was to assess the adequacy of the representation of the local SES, highlighting missing elements and incorrect dynamics. It involved a forest technician, an agronomist and a naturalist-biologist, all working for the CFC. They were chosen for their expertise in the relative fields and their direct experience of the local

context, including socio-economic dynamics.

The game was then reviewed through two pilot sessions. The first one involved only researchers in geography and fire management disciplines, while the second one involved both researchers and a forest technician from the CFC. The pilot sessions aimed at assessing the scientific correctness of the dynamics represented and the game's playability, including the appropriateness of time management in the different game phases and of the supporting materials. These pilot sessions allowed for improvements both to the gameplay and to the ABM code.

2.3. The game sessions

Three game sessions were organised in the valley, with the collaboration of the mayors of the municipalities where they were held. The municipalities (named A, B and C from now on to anonymise participants) were located one at the bottom of the valley, one in the middle and one in the upper part. The collaboration with the mayors was crucial for the involvement of the participants: stakeholders involved in local land and fire management, belonging to the same categories listed in Section 2.2.1, plus local forest and naturalist experts, and citizens particularly interested in the topic of the game (Fig. 3). Each participant, while bringing their personal expertise to the participatory activity, was asked to choose a role in the game that differed from the one they had in real life.

Each session was led by a facilitator and structured with a preparation phase (presentations, instructions, role assignment, and game material allocation), a play phase, and a debriefing phase. According to Crookall (2010), debriefing is "the occasion and activity for the reflection on and the sharing of the game experience to turn it into learning". It consists of a structured discussion about what happened during the game and how to relate it to the participants' real-life experiences (Adolph et al., 2023). The facilitator encouraged the discussion by asking relevant questions to the group, starting by sharing observations of participants' spoken remarks, actions and behaviour during the gameplay. Some quantitative plots derived from the ABM simulation were also used. See the Supplementary Material for the guideline questions used for the debriefing discussion.

The game sessions were entirely recorded with a video camera and a recording microphone. The analysis of the recorded material and the real-time observation notes made by researchers aimed at understanding the behaviours of the players, their strategies in the game, their corresponding actions in the real world, their point of view on management issues, the challenges they face in their real-world roles, and their vision of the local SES. The focus was also on assessing *A Picit Jeu* effects on enhancing the discussion, facilitating mutual understanding, and sharing of information. An observation protocol was developed as a guideline (see the Supplementary Material).

2.4. The process evaluation

In addition to the direct observation and the feedback collected during the debriefing, an evaluation survey made of a mix of open and Likert-scale questions was administered to the participants at the end of each session. The survey focused on how players felt during the game, on the perceived utility of the experience, on the adequateness of the game for facilitating the discussion and understanding other stakeholders' opinions, and on the opportunity for the players to learn and share new insights on the SES dynamics (see Fig. 1 in the Supplementary material for the complete list of questions).

Finally, five semi-structured interviews were conducted approximately two years after the game sessions, to assess the potential long-term direct and indirect impacts of the process on local collaborations and initiatives. The interviewees were the director forest technician of the CFC, the leader of a volunteer firefighter team, two mayors, and a member of an environmental association, all of whom had participated in the game sessions.

3. Results

3.1. Game overview

The analysis of the initial interviews with local stakeholders pointed out seven thematic areas. In Table 1 we summarize the focus of each thematic area, the specific issue directly or indirectly related to wildfire prevention in Valchiusella, and its translation into game purposes.

In order to allow participants in game sessions to collectively analyse and discuss dynamics and challenges they face in real life, it is crucial that the challenges and mechanics represented in the game correspond to those the players deal with in their real life in the specific context. The game design was then guided by the content of the interviews, while the various review steps described in Section 2.2.5 ensured appropriate representation of the local SES and scientific accuracy of the game content. Therefore, the seven thematic areas guided the definition of the SES conceptual model based on the ARDI steps and, later, its translation into game elements and mechanics. For clarity, Fig. 4 shows the components of the SES conceptual model already represented according to game mechanic categories instead of original ARDI categories: players' roles (instead of actors), land resources, players' interactions, and player-resource interactions.

Four game roles were identified:

- The municipal administration, represented by the mayor, who delegates the management of forest parcels to the technician of the forest consortium and rents the public pasture parcels to the farmers;
- The forest consortium, represented by a technician, who is in charge of managing (i.e. cutting and thinning) public forest;

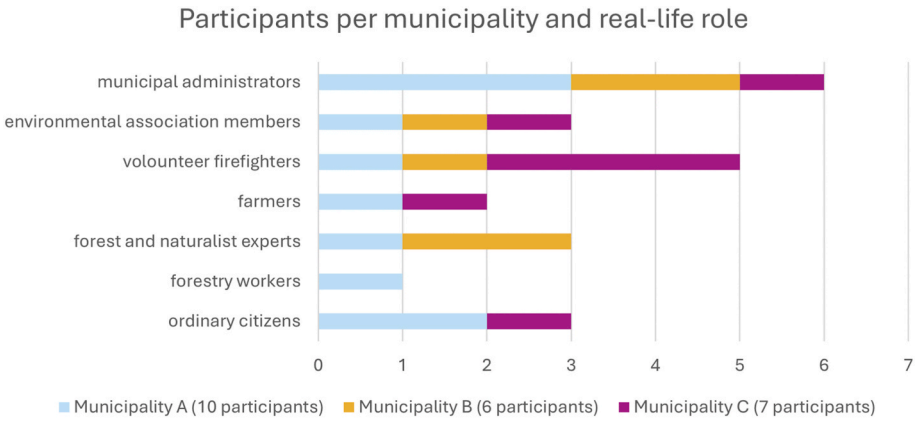

Fig. 3. Categories of stakeholders participating in each game session.

Table 1
Correspondence between thematic areas, issues related to wildfire prevention and game focus.

Thematic area	Wildfire prevention issue	Game purpose
1. Economic sphere	Forest management and territorial management are now less economically sustainable than in the past.	Enhancing discussion between the different stakeholders about how to manage forest lands in an economically sustainable way.
2. Planning	Long-term and valley-level planning are often missing in Valchiusella.	Promoting discussion between decision makers about a long-term and valley-level planning project.
3. New generations	People in the valley, and specifically new generations, often are not aware of the role of territorial management in wildfire risk mitigation.	Raising awareness among the population about these topics.
4. Intergroup conflicts	Conflicts between old residents and new inhabitants exist.	Helping dialogue between different groups of inhabitants and facilitating mutual understanding.
5. Ecological sensitivity	The interactions between ecological dynamics and socioeconomic activities are not always clear for all people.	Helping participants understand interactions between the natural ecosystem and the socio-economic system.
6. Rural abandonment	Land abandonment is a major issue, mainly for private forest parcels.	Reducing private forest parcel abandonment by promoting their collective management.
7. Wildfires	The effects of rural abandonment on fire risk are not clear for all inhabitants.	Helping participants understand the effects of rural abandonment on fire risk and the need to manage it.

- Farmers, who graze their cow herds on public pastures that they rent. One or two farmers can be in the game.
- Private forest owners, who manage their own forest parcel. Three forest owners are in the game.

During the game, the mayor and the technician of the forest consortium must agree on the management plan of public forests and on how to share the economic costs for thinning and the economic gains for cuts. The mayor and the farmers must negotiate the price for renting public pastures. The private forest owners can ask the forest technician for technical information, such as the stumpage value of their parcel. The forest technician is also able to assess each land parcel's wildfire hazard and can decide to share this information with the other players.

Three kinds of land resources were identified: forests, pastures and pioneer shrublands. These were used for characterizing the space represented by the ABM, made of 20 land parcels (Fig. 5). A number of functions representing the action of the players on the land parcels were coded in the ABM: cutting and thinning the forest parcels, grazing the pasture parcels, building or maintaining the huts of the pasture parcels, converting to forest, or to pasture the pioneering shrubland parcels.

Three kinds of dynamics were also identified in the SES:

- Ecological dynamics:
  1. The natural reforestation of abandoned pastures, which leads to the growth of a more flammable pioneer vegetation;
  2. The behaviour of fire, which is more likely to burn more flammable lands than others;
  3. Fire hazard dependence on climate conditions;
- Social dynamics:
  4. The common lack of interest on the part of private forest owners in their parcels, which usually leads to their abandonment;
- Economic dynamics:
  5. The pastoral products market variations;
  6. The variation in the cost of forest operations, such as cut and thinning, and of wood prices because of market changes;

These dynamics were crucial in characterizing the ABM. According to dynamic 1, ungrazed pasture parcels become pioneer shrubland after some rounds. Dynamic 2 was used to code the fire behaviour in case of ignition. Dynamic 4 was used to code the behaviour of four autonomous agents representing private forest owners. Dynamics 3, 5 and 6 were translated as possible scenarios to be set at the beginning of the ABM simulation.

Finally, a time duration of 50 years was chosen for the game, as a relevant amount of time from a silvicultural point of view. The players are asked to take actions every 10 years, for a total of five game rounds. Between each round, the ABM simulates forest growth and the effects of their actions on the land parcels. Moreover, at the beginning of the third

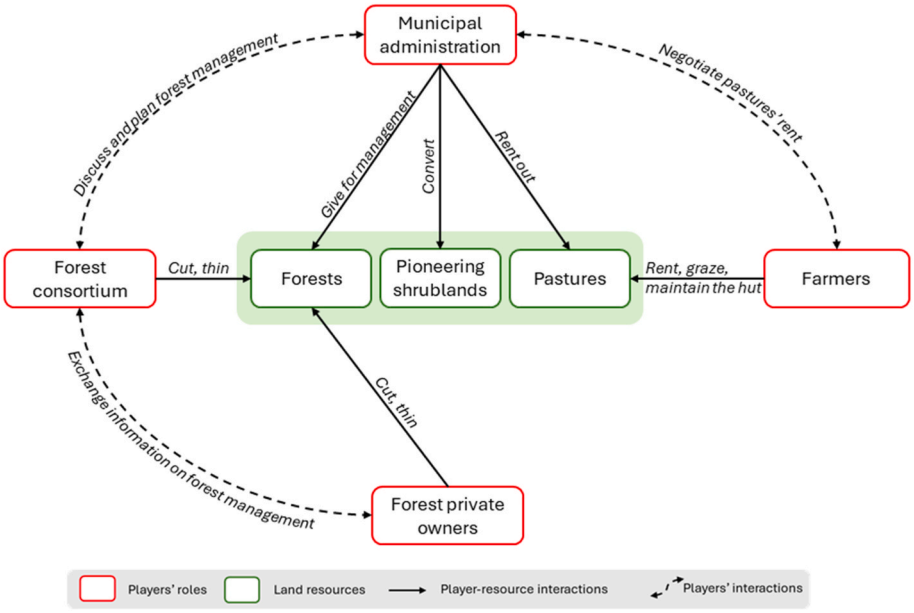

Fig. 4. Overview of the game roles, land resources and interactions.

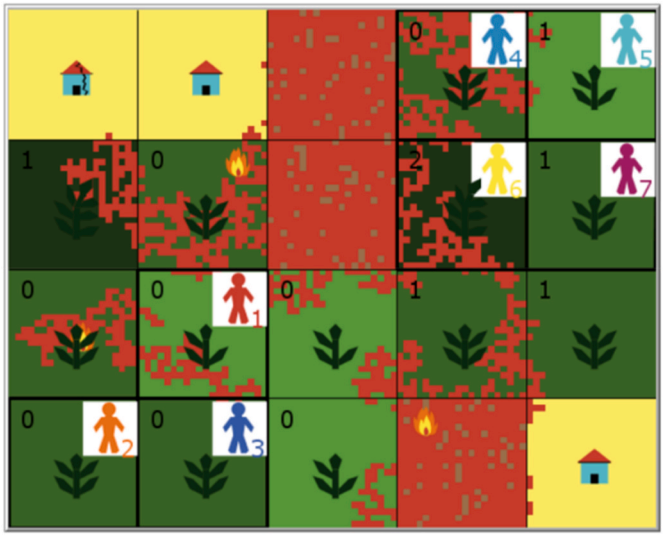

Fig. 5. Screenshot of the interface of the ABM, used as the 'board' of the game. The colours of the land parcels correspond to the three different land use types and to the age of forests. The house icons represent huts on the pastures. The human figures identify the forest parcels owned by the private owner players and by the autonomous agents. Three fires have spread on the landscape in the simulation represented. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

or fourth round, the model simulates the behaviour of three wildfires, ignited randomly on the landscape. More thinned and younger forests are less likely to burn than older and less thinned (or unthinned) ones, while pioneer shrublands are the most likely to burn (see ODD description for more details, Vigna and Millington, 2024). During the game, the players have to deal simultaneously with the economic constraints imposed by their limited resources and the cost of their actions, and with the impact of their management decisions on the likelihood that wildfire events will affect land parcels.

3.2. Game sessions' outcomes

During the three game sessions, the level of involvement in the activity and amusement of the participants was generally high. The mean score in the answers to the question "Did you have fun" in the final survey was 6.3 on a 1 to 7 Likert scale (see Fig. 1 in the Supplementary material for a complete overview of answers to the final questionnaires). However, some participants were more active than others. This was particularly evident in Municipality A, where some participants took a driving role in the collective decisions, while some remained more in the background and expressed less. The Municipality A session involved a higher number of participants compared to the other two, which could, in part, explain this fragmentation in participants' involvement. Moreover, existing friendship links were discernible in the group and tended to affect the interactions in the game.

In addition, in Municipality A and B the mayors had a very active and central role in game interactions. This is partly explained by the fact that, in both situations, the mayor was playing the role of the forest technician, which is particularly influential in the game mechanics. Moreover, their real-life leadership role probably influenced their role in the game.

For some participants it was also easier to understand the game rules and mechanics than for others, placing them in an advantageous position. This advantageous position allowed them to be more influential in the collective decision-making and to guide the discussions. The mean score of the question "Was it easy to understand the rules of the game?" on a 1 to 7 Likert scale was 6.3 in Municipality A (median value: 6), 6.7 in Municipality B (median value: 7) and 4.8 in Municipality C (median value: 5.5). In Municipality C, no participant adopted a guiding role in the discussions and the group generally complained about the short time available for discussing the implications of the activity during the debriefing phase, since it took them a long time in the beginning to understand the game functioning. Time constraint was generally an issue. All the sessions took place in the evening, to allow the participation of all stakeholders, particularly farmers whose work does not include days off. However, this choice reduced the time available, often at the expense of the debriefing phase.

The exchange of roles was generally perceived as very helpful. As an example, the forest technician playing the role of the mayor in Municipality A session declared during the debriefing that he found that *"the difficulty of this is that you have to interact with multiple stakeholders at the same time. You have to deal with many people and issues simultaneously, which differs from my situation. Money comes in one way and goes out another, and, in the end, it all goes out! This is maybe something trivial, but I was able to experience it this evening."* In this regard, the absence of some crucial stakeholders in some sessions limited the outcomes. More specifically, in Municipality B the participants largely discussed the role of modern farming techniques and a general lack of care in land maintenance on the farmers' side in contributing to the expansion of the pioneering shrubland on pastures. However, no farmers were present in the session to contribute their points of view and highlight their challenges. In Municipality C, the role of CFC in Valchiusella was unclear to most participants, but the absence of CFC technicians prevented a helpful exchange of information on this point.

The game proved to be an effective tool in helping the discussion about land management issues and strategies. The participants were able to identify and analyse the challenges for a fire-resilient landscape in Valchiusella, such as land fragmentation, obstacles to stakeholders' collaboration, and controversial drives of European funding. Land fragmentation was identified as a major driver of land abandonment, since it challenges large-scale planning of the landscape. Concerning obstacles to collaboration, participants identified two main elements: the scarcity of economic resources and a cultural aspect. Resource constraints force stakeholders to focus on their short-term economic sustenance instead of long-term and shared plans, whereas the local culture places a solid value on private properties, especially forests. Private forests are sometimes exploited for family firewood consumption but are more often not managed at all. However, owners are frequently unwilling to give up the right to manage their parcels, even when they are not interested in doing so themselves: the land is not transferable because it was inherited from ancestors, belongs to the family, and will go to their children. This phenomenon doesn't concern new inhabitants of the valley, who are likely to be more open to forms of collective parcel management, such as Land Consolidation Associations (Beltramo et al., 2018). Finally, on one side, the direct funding to farming activities linked to the Common Agricultural Policy helps to keep this traditional practice on the land, also enabling young people to start their pastoral activity; on the other side, it pushes farmers to expand the herd and graze a large extent, without keeping attention to the sustainable management of pasture, since the grazed area is the only parameter deciding the amount of funding.

The game sessions were also helpful in brainstorming possible strategies to directly or indirectly help the creation of a fire-resilient landscape. For example, a participant expressed the need to diversify the spatial distribution of land cover, in line with findings about the role of landscape spatial heterogeneity in reducing the spread and intensity of fires (Parsons et al., 2017; Vacchiano et al., 2021). This is challenged by the widespread abandonment of private parcels and thus the transition from a complex alternation of open spaces and different densities of forest cover to a more homogeneous and dense forest cover. Another participant suggested the use of prescribed fire and experimental fire prevention action. Moreover, different forms of collective management concerning pastoralist activity came out during the debriefing phases, such as a community-based cooperative for obtaining other kinds of

European funding for land management and development, a solidarity buying group for shortening the supply chain between producers and consumers of milk products, and a valley consortium dairy for lowering the cost for farmers to transform milk into cheese.

3.3. Long-term evaluation

The interviews carried out *circa* two years later are part of the attempt to evaluate the effect of the experience from a broader point of view than individual game sessions, considering the game not only as a tool to facilitate discussion on the spot, but also as a positive process trigger for longer-term change. This is linked to the use of the game experience to raise awareness among the participants about the importance of a shared planning strategy and effective land management activities, and to foster interactions and collaboration.

The outcomes of the interviews proved some long-term positive effects on the collaboration among the CFC and the other stakeholders, specifically in one of the municipalities, some private owners, and the volunteer forest firefighting teams of the valley. However, they also highlighted a different perception and awareness among the interviewees of the game sessions' role in facilitating this positive process, as well as the difficulty of entirely attributing it to the game experience. For example, a stronger collaboration between the CFC and the firefighting teams was brought to the partnership via a financed local development project linked to fire risk. According to the CFC director forest technician, this was made possible by the participation of both in the game sessions and, also, in an event organised one year later for sharing the research results with the local community. However, according to the firefighting team leader, it is difficult to exclude that it would have happened anyway and that a positive process was already ongoing.

Interestingly, the experience did not seem to have positively impacted the interactions between the CFC and the local environmental associations. Both the director of the CFC and the environmental association member referred to the creation of a new association during the two-year period by this latter actor and some other local citizens, all new inhabitants of the valley, with the expressed aim of preserving local forests from exploitation. Its members often denounce the CFC actions as part of an exploitation process and complain about the lack of consideration for their point of view. The conflict thus seems to have worsened in this case.

Finally, a positive effect was found in the interactions between the CFC and the University of Turin institution itself, thanks to the involvement of the CFC technicians not only in the game sessions but also in the review steps of the development process. Other collaborative activities have since been carried out.

Table 2 summarizes the main points presented in the Results section, by highlighting the positive outcomes and long-term effects of the process, as well as its challenging aspects.

Table 2
Summary of the positive outcomes of the game sessions, the long-term effects of the process and its challenging aspects.

Positive outcomes and long-term effects	Challenging aspects
High involvement of the participants	Different level of participants' contribution to the discussions
Understanding of other roles' challenges	Difficulties in understanding the game rules
Identification of the challenges for a fire-resilient landscape	Time constraints
Identification of direct and indirect strategies for a fire-resilient landscape	Lack of stakeholders' representation in some game sessions
Enhanced collaboration between some stakeholders	Uneven enhancement of collaboration and awareness of the process
Enhanced collaboration between the CFC and the university of turin	

4. Discussion

A Picit Jeu game sessions demonstrate the multifaceted results that can come from the collaborative process of serious gaming, which allows both the researchers and the players to learn. The participants' discussions drew our attention to some issues affecting the SES, on which planning strategies need to focus across different scales, such as the organisation of pastoral funding, the attitude of the inhabitants toward collective management, and the lack of information about CFC activities and opportunities for forest owners. At the same time, the game sessions gave stakeholders the opportunity to identify these issues, question their points of view and start a dialogue, sometimes also resulting in strengthened collaborations. The observation of the sessions and the outcomes of the evaluation interviews allow us to discuss some focal points and identify more general lessons valuable for others using serious gaming to negotiate or inspire collaboration between stakeholders in developing fire-resilient (or otherwise sustainable) landscapes.

First, a significant effort needs to be made in defining the group of participants. In this work, the game sessions were organised in collaboration with the mayors of the municipalities, who oversaw the invitation of the participants, leaving the researcher a lower control over their selection As explained by Barreteau et al. (2010), a requisite for the success of a participatory processes as ComMod is that the participants in the collective action dynamics accept them to the point of participating in them. What makes this possible is very often a local anchoring, which is provided by the social capital of those who are promoting the process. The help from the village mayors, who have a dense relation network in the area, allowed us to successfully reach out to stakeholders that would have been less likely to respond to our direct invitation, overcoming people's scepticism toward a novel methodology and generating interests and curiosity instead. Even if the mayors were in charge of disseminating the invites, we put in place two measures for assuring appropriate representativeness of the stakeholders: first, the mayors were all provided with a list of stakeholder categories that needed to be involved; second, when the mayors were unable or uncomfortable in inviting people from one or more categories, the researchers did it. This was the case, for example, of the members of the local environmental associations, who are often new inhabitants of the valley and whose presence in two of the three game sessions was assured by a direct invitation from the researchers.

However, despite these measures the difficulty of involving a representative of each category in all the sessions caused some unevenness in the composition of the groups, as highlighted in the Results section. The participants criticized this unevenness both during the debriefings and in the evaluation interviews.

Related to the previous point, in two game sessions, a certain power imbalance between the participants was felt, as the mayors were particularly influential on the game dynamics, helped also by the role they were assigned. Power relations influencing the game is a crucial point in this kind of experience and needs great attention and effort from the facilitator (Garcia et al., 2022). Similarly, pre-existing relationships between the participants can make someone feel more entitled to express their opinion to the group than others. Stakeholders with a stronger power position can impose their ideas on the discussions and ignore others, while a lack of self-confidence, freedom of expression or understanding of the issues at stake can limit a player's ability to defend their interests (Barnaud et al., 2010). In this work, a more attentive choice of the game roles would have benefited the group dynamics, by deliberately assigning less influential roles to the participants with more influential roles and leadership attitudes in the real world. This is supported by the fact that no power imbalance was witnessed in the Municipality C game session, where the mayor played the less influential role of a private forest owner.

The second lesson learned concerns the inclusion of the game sessions in a broader participatory process. The ComMod approach from

which this work was inspired clearly places the use of the game simulations as only one of the steps of a structured participatory process (Daré et al., 2015). Stakeholders generally engage actively in this modelling process from the early stages (Basco-Carrera et al., 2018). The benefit of involving stakeholders in designing the model on their perceived legitimacy of the model outcomes is well documented in the literature (Van Berkel and Verburg, 2012), and the challenges for evaluating models where this is not the case have also been demonstrated (Millington et al., 2011). This allows the decision-makers to take ownership of the model, which is a requirement for the success of the process (Joffre et al., 2015). This process, however, takes time. Because of the limited resources, we chose to involve only the CFC technicians in ABM and game design. During gaming sessions no player ever directly questioned the representation of the local SES in *A Picit Jeu* in terms of ecological or socio-economic dynamics. However, two criticisms were raised during the debriefings: that the game mechanics (i) push the players to focus on the economic value of forests and pastures at the expense of other kinds of values, and (ii) could transmit the message that assigning uses other than "wood production" to forests (for example by creating a protected area with no cutting activities allowed) is always negative, since the ABM fire behaviour simulation rewards the owner of young and thinned forests more than the owner of old and not managed ones. These two aspects could have been taken into consideration in the game development if all the stakeholders had been involved in the creation process.

Moreover, we argue here that the benefits of involving stakeholders from the modelling step go beyond the legitimation of the game session's results and concerns also other less tangible outcomes, such as the enhancement of networks and collaborations and the perceived consideration for one's perspective in the collective debate. The long-term evaluation interview highlighted the benefits perceived by the CFC director forest technician on the interactions between the CFC and other local stakeholders, as well as the University of Turin. This was made possible by the involvement of the CFC technicians in the whole process, from the revision steps to the sharing of the process results with the local community. Their involvement allowed them to have a clear understanding of the whole process and its objectives, and so benefit from it by strengthening the collaborations with other stakeholders of interest. On the contrary, the environmental association members were only invited to attend the game sessions and later stated that the experience didn't have any positive effects on making their voices heard in local land management debates. An intermediary situation concerns the firefighting team leader, who described the improvement in the collaboration with the CFC in the two years following the game sessions, but, contrary to the forest technicians, didn't think that *A Picit Jeu* experience influenced it. These very different opinions suggest that not only acquiring ownership of the model and game tools is crucial, but also acquiring ownership of the entire process can enhance the benefits of the process itself and provide the stakeholders with a greater awareness of them.

A significant limitation of this work is that all three game sessions were organised at the municipal level, involving almost exclusively residents of one municipality at a time. The lack of a common perspective at the valley level on landscape planning was one of the issues identified in the initial interviews. Promoting the discussion between decision-makers about valley-wide planning projects was included in the game purposes during the initial development phase (see Table 1). However, the absence of leadership at the valley level, which would have been fundamental in setting the meeting and inviting the participants, prevented the organisation of a game session involving more geographically distributed participants. This precluded the exchange of points of view and the development of a shared perspective across a larger extent than a single municipality. Future developments in this methodology should address this point. A game session involving all the valley's mayors could be a starting point, followed by game sessions bringing together lower-level actors from multiple municipalities to avoid the power imbalance issues mentioned above.

Another limitation concerns the challenges in assessing the effects of the process. Literature on serious gaming interventions indicates a general lack of assessment procedures that consider the overarching objective of the process, instead of learning at the individual level (Rodela and Speelman, 2023). Moreover, serious games are usually evaluated in a short period, with assessment procedures implemented no more than a few months after the sessions (Calderón and Ruiz, 2015). However, the complex nature of their outcomes drove us to try to evaluate the impact from a broader perspective than just the results of collective discussions at individual sessions. A longer time scale assessment was then necessary. The interviews highlighted interesting focal points almost two years after the game sessions. However, the impossibility of isolating the effects of the serious game experience from the impacts of other events that occurred in the two years makes it challenging to attribute developments in the local context with certainty. The assessment of this kind of process is made especially difficult by the impossibility of comparing outcomes with a control sample, since finding another context with the same exact components and challenges is impossible. Nevertheless, it is essential to note that the evaluation was carried out by focusing on the perception of the stakeholders themselves rather than on an objective analysis of changes, with the aim of eliciting once again their perspective.

5. Conclusions

In this work, we aimed to contribute to the literature on fire-resilient landscapes by addressing the need for integrated planning approaches through the activation of sustainable processes over time. We have presented a methodology inspired by the ComMod approach to support stakeholders in exploring land management strategies for landscape fire-resilience. The methodology entails a participatory process that combines agent-based modelling and serious gaming. It was tested in Valchiusella, an Italian alpine valley. Twenty-three local stakeholders were involved in collective discussions on land management scenarios for fire prevention through the serious game A Picit Jeu.

During the game sessions, the participants identified and discussed the challenges for a fire-resilient landscape in Valchiusella, such as land fragmentation and land abandonment, stakeholders' limited collaboration due to scarcity of economic resources and cultural value of private property, and controversial drives of European funding. Possible strategies to help the creation of a fire-resilient landscape also emerged, mainly related to different forms of collective management in pastoralist activities, to prevent land abandonment and maintain diversity in the spatial distribution of land cover.

The observation of the game sessions and the information collected through a multi-step evaluation procedure confirmed the methodology's potential not only to facilitate discussion among different stakeholders but also as a positive process trigger for longer-term change. While the challenges and strategies for a fire-resilient landscape identified can be transferrable to other contexts characterized by similar processes of land abandonment and a similar stakeholder composition, such as other Alpine valleys, the enhanced collaboration among stakeholders requires the replication of the entire participatory process.

The discussion of the outcomes of this experience, moreover, allowed us to point out some recommendations for future works using serious gaming to support the collaboration of stakeholders in developing sustainable landscapes. First, aiming for an even composition of session groups, where all real-life roles are represented, is crucial. Second, the group composition needs to take into account the multiple levels of organisation in the area by involving participants across them, to bring the discussion to the wider landscape spatial scale (e.g. valley level instead of just municipality level). In addition, careful considerations are needed about the allocation of game roles to disrupt power dynamics and allow all the participants to contribute to the debate actively. For example, avoiding allocating an influential game role to a participant

with a real-life leadership role could be beneficial. Finally, we suggest aiming for the involvement of the broader stakeholder spectrum in developing the game itself, as participation in the entire process has proven to strengthen collaboration between participants.

CRediT authorship contribution statement

Ingrid Vigna: Writing – original draft, Methodology, Investigation, Conceptualization. **James Millington:** Writing – review & editing, Methodology, Conceptualization. **Davide Ascoli:** Writing – review & editing, Investigation. **Elena Comino:** Supervision, Investigation, Conceptualization. **Alessandro Pezzoli:** Supervision, Conceptualization. **Angelo Besana:** Supervision, Conceptualization.

Declaration of competing interest

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

Data availability

The code which the manuscript refers to has been shared on Comses library and the link is provided in the manuscript.

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Appendix A. Supplementary data

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References

Adolph, B., Jellason, N.P., Kwenye, J.M., et al., 2023. Exploring farmers' decisions on agricultural intensification and cropland expansion in Ethiopia, Ghana, and Zambia through serious gaming. Land 12, 556. https://doi.org/10.3390/land12030556.

Ascoli, D., Moris, J.V., Marchetti, M., Sallustio, L., 2021. Land use change towards forests and wooded land correlates with large and frequent wildfires in Italy. Annals of Silvicultural Research 46. https://doi.org/10.12899/asr-2264.

Ascoli, D., Plana, E., Oggioni, S.D., et al., 2023. Fire-smart solutions for sustainable wildfire risk prevention: bottom-up initiatives meet top-down policies under EU green deal. Int. J. Disaster Risk Reduc. 92, 103715 https://doi.org/10.1016/j.ijdrr.2023.103715.

Ascoli, D., Vacchiano, G., Scarpa, C., et al., 2020. Harmonized dataset of surface fuels under Alpine, temperate and Mediterranean conditions in Italy. A synthesis supporting fire management. iFor. Biogeosci. For. 13, 513. https://doi.org/10.3832/ifor3587-013.

Bacciu, V., Sirca, C., Spano, D., 2022. Towards a systemic approach to fire risk management. Environ. Sci. Pol. 129, 37–44. https://doi.org/10.1016/j.envsci.2021.12.015.

Backlund, P., Engstrom, H., Hammar, C., Johannesson, M., Lebram, M., 2007. Sidh–a game based firefighter training simulation. In: 11th International Conference Information Visualization, IV'07. IEEE, pp. 899–907.

Barnaud, C., d'Aquino, P., Daré, W., et al., 2010. Les asymétries de pouvoir dans les processus d'accompagnement. In: Etienne, M. (Ed.), La modélisation d'accompagnement: une démarche participative en appui au développement durable. Quae, pp. 125–152.

Barreteau, O., Bousquet, F., Etienne, M., Souchère, V., d'Aquino, P., 2010. La modélisation d'accompagnement: une méthode de recherche participative et adaptative. La modélisation d'accompagnement: une démarche en appui au développement durable. Paris (France): Quae éditions, pp. 21–46.

Basco-Carrera, L., Meijers, E., Sarısoy, H.D., et al., 2018. An adapted companion modelling approach for enhancing multi-stakeholder cooperation in complex river basins. Int. J. Sustain. Dev. World Ecol. 25, 747–764. https://doi.org/10.1080/13504509.2018.1445668.

Beltramo, R., Rostagno, A., Bonadonna, A., 2018. Land consolidation associations and the management of territories in harsh Italian environments: a review. Resources 7, 19. https://doi.org/10.3390/resources7010019.

Bowman, D.M.J.S., O'Brien, J.A., Goldammer, J.G., 2013. Pyrogeography and the global quest for sustainable fire management. Annu. Rev. Environ. Resour. 38, 57–80. https://doi.org/10.1146/annurev-environ-082212-134049.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3, 77–101. https://doi.org/10.1191/1478088706qp063oa.

Calderón, A., Ruiz, M., 2015. A systematic literature review on serious games evaluation: an application to software project management. Comput. Educ. 87, 396–422. https://doi.org/10.1016/j.compedu.2015.07.011.

Canadas, M.J., Novais, A., Marques, M., 2016. Wildfires, forest management and landowners collective action: a comparative approach at the local level. Land Use Pol. 56, 179–188. https://doi.org/10.1016/j.landusepol.2016.04.035.

Caroca, J., Bruno, M.A., Aldunate, R.G., Arancibia, C.U., 2019. Epistemic video game for education in wildfire response: a pilot study. Int. J. Technol. Enhanc. Learn. (IJTEL) 11 (3), 247–258.

Charnley, S., Spies, T.A., Barros, A.M.G., et al., 2017. Diversity in forest management to reduce wildfire losses: implications for resilience. E&S 22, art22. https://doi.org/10.5751/ES-08753-220122.

Crookall, D., 2010. Serious games, debriefing, and simulation/gaming as a discipline. Simulat. Gaming 41, 898–920. https://doi.org/10.1177/1046878110390784.

Daré, W., Venot, J.-P., Le Page, C., 2015. La modélisation d'accompagnement : partager des représentations, simuler des dynamiques.

Etienne, M., 2009. Co-construction d'un modèle d'accompagnement selon la méthode ARDI : guide méthodologique.

Etienne M, Du Toit DR, Pollard S (2011) ARDI: a Co-construction method for participatory modeling in natural resources management. Ecol. Soc. 16.

Fernandes, P.M., 2013. Fire-smart management of forest landscapes in the Mediterranean basin under global change. Landsc. Urban Plann. 110, 175–182. https://doi.org/10.1016/j.landurbplan.2012.10.014.

Flood, S., Cradock-Henry, N.A., Blackett, P., Edwards, P., 2018. Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. Environ. Res. Lett. 13, 063005 https://doi.org/10.1088/1748-9326/aac1c6.

Garcia, C.A., Savilaakso, S., Verburg, R.W., et al., 2022. Strategy games to improve environmental policymaking. Nat. Sustain. 5, 464–471. https://doi.org/10.1038/s41893-022-00881-0.

Grimm, V., Berger, U., Bastiansen, F., et al., 2006. A standard protocol for describing individual-based and agent-based models. Ecol. Model. 198, 115–126. https://doi.org/10.1016/j.ecolmodel.2006.04.023.

Ji, X., Wang, F., Zheng, H., Nie, X., 2024. Enhancing emergency decision-making skills through game-based learning: a forest fire simulation exercise game. InInternational Conference on Human-Computer Interaction. Springer Nature Switzerland, Cham, pp. 145–159.

Joffre, O.M., Bosma, R.H., Ligtenberg, A., et al., 2015. Combining participatory approaches and an agent-based model for better planning shrimp aquaculture. Agric. Syst. 141, 149–159. https://doi.org/10.1016/j.agsy.2015.10.006.

Johns, M.J., Ezenwa, E.C., Lee, S., Maiorana, T., Wood, C., Levano, J.D., Tesfay, R.A., Takami, M., Dodd, C.A., Li, M., Manning, H., 2024. Participatory design of a serious game to improve wildfire preparedness with community residents and experts. InExtended Abstracts of the CHI Conference on Human Factors in Computing Systems 1–8.

Kirschner, J.A., Clark, J., Boustras, G., 2023. Governing wildfires: toward a systematic analytical framework. Ecol. Soc. 28 https://doi.org/10.5751/ES-13920-280206.

Kline, J.D., White, E.M., Fischer, A.P., et al., 2017. Integrating social science into empirical models of coupled human and natural systems. E&S 22, art25. https://doi.org/10.5751/ES-09329-220325.

Kravari, K., Bassiliades, N., 2015. A survey of agent platforms. JASSS 18, 11.

MacDonald, D., Crabtree, J.R., Wiesinger, G., et al., 2000. Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. J. Environ. Manag. 59, 47–69. https://doi.org/10.1006/jema.1999.0335.

Madani, K., Pierce, T.W., Mirchi, A., 2017. Serious games on environmental management. Sustain. Cities Soc. 29, 1–11. https://doi.org/10.1016/j.scs.2016.11.007.

Millington, J.D.A., Romero-Calcerrada, R., Wainwright, J., Perry, G.L.W., 2008. An agent-based model of Mediterranean agricultural land-use/cover change for examining wildfire risk. J. Artif. Soc. Soc. Simulat. 11 (4), 4. https://jasss.soc.surrey.ac.uk/11/4/4.html.

Millington, J.D.A., Demeritt, D., Romero-Calcerrada, R., 2011. Participatory evaluation of agent-based land-use models. J. Land Use Sci. 6, 195–210. https://doi.org/10.1080/1747423X.2011.558595.

Moreira, F., Ascoli, D., Safford, H., et al., 2020. Wildfire management in Mediterranean-type regions: paradigm change needed. Environ. Res. Lett. 15, 011001 https://doi.org/10.1088/1748-9326/ab541e.

Otero, I., Castellnou, M., González, I., Arilla, E., Castel, L., Castellví, J., et al., 2018. Democratizing wildfire strategies. Do you realize what it means? Insights from a participatory process in the Montseny region (Catalonia, Spain). PLoS One 13 (10), e0204806. https://doi.org/10.1371/journal.pone.0204806.

Pais, S., Aquilué, N., Campos, J., et al., 2020. Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. Ecosyst. Serv. 44, 101143 https://doi.org/10.1016/j.ecoser.2020.101143.

Parsons, R.A., Linn, R.R., Pimont, F., et al., 2017. Numerical investigation of aggregated fuel spatial pattern impacts on fire behavior. Land 6, 43. https://doi.org/10.3390/land6020043.

Pereira, G., Prada, R., Paiva, A., 2014. Disaster prevention social awareness: the stop disasters! case study. In: 2014 6th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES). IEEE, pp. 1–8.

Pulido, F., Corbacho, J., Bertomeu, M., et al., 2023. Fire-Smart Territories: a proof of concept based on Mosaico approach. Landsc. Ecol. 38, 3353–3370. https://doi.org/10.1007/s10980-023-01618-w.

Ribeiro, P.F., Moreira, F., Canadas, M.J., et al., 2023. Promoting low-risk fire regimes: an agent-based model to explore wildfire mitigation policy options. Fire 6, 102. https://doi.org/10.3390/fire6030102.

Rodela, R., Ligtenberg, A., Bosma, R., 2019. Conceptualizing serious games as a learning-based intervention in the context of natural resources and environmental governance. Water 11, 245. https://doi.org/10.3390/w11020245.

Rodela, R., Speelman, E.N., 2023. Serious games in natural resource management: steps toward assessment of their contextualized impacts. Curr. Opin. Environ. Sustain. 65, 101375 https://doi.org/10.1016/j.cosust.2023.101375.

Ruankaew, N., Le Page, C., Dumrongrojwattana, P., et al., 2010. Companion modelling for integrated renewable resource management: a new collaborative approach to create common values for sustainable development. Int. J. Sustain. Dev. World Ecol. 17, 15–23. https://doi.org/10.1080/13504500903481474.

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Liberta, G., Oom, D., Branco, A., De Rigo, D., Suarez Moreno, M., Ferrari, D., Roglia, E., Scionti, N., Broglia, M., 2024. Advance Report on Forest Fires in Europe, Middle East and North Africa 2023. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/74873,JRC137375, 2024.

Spadoni, G.L., Moris, J.V., Vacchiano, G., et al., 2023. Active governance of agro-pastoral, forest and protected areas mitigates wildfire impacts in Italy. Sci. Total Environ. 890, 164281 https://doi.org/10.1016/j.scitotenv.2023.164281.

Speelman, E., van, N., Garcia, C., 2018. Gaming to Better Manage Complex Natural Resource Landscapes.

Spies, T.A., White, E., Ager, A., et al., 2017. Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. E&S 22, art25. https://doi.org/10.5751/ES-08841-220125.

Tedim, F., Leone, V., Xanthopoulos, G., 2016. A wildfire risk management concept based on a social-ecological approach in the European Union: *fire Smart Territory*. Int. J. Disaster Risk Reduc. 18, 138–153. https://doi.org/10.1016/j.ijdrr.2016.06.005.

Thacker, F.E.N., Ribau, M.C., Bartholomeus, H., Stoof, C.R., 2023. What is a fire resilient landscape? Towards an integrated definition. Ambio 52, 1592–1602. https://doi.org/10.1007/s13280-023-01891-8.

United Nations Environment Programme, 2022. Spreading like wildfire – the rising threat of extraordinary landscape fires. A UNEP Rapid Response Assessment. Nairobi.

Vacchiano, G., Berretti, R., Motta, R., Ascoli, D., 2021. Selvicoltura Preventiva Prossima Alla Natura.

Valese, E., Conedera, M., Held, A.C., Ascoli, D., 2014. Fire, humans and landscape in the European Alpine region during the Holocene. Anthropocene 6, 63–74. https://doi.org/10.1016/j.ancene.2014.06.006.

Van Berkel, D.B., Verburg, P.H., 2012. Combining exploratory scenarios and participatory backcasting: using an agent-based model in participatory policy design for a multi-functional landscape. Landsc. Ecol. 27, 641–658. https://doi.org/10.1007/s10980-012-9730-7.

Vigna, I., Millington, J.D.A., 2024. A Picit Jeu: an agent-based model for role-playing game. CoMSES Computational Model Library. Retrieved from, Version 1.0.0. https://www.comses.net/codebases/50849361-642c-48ed-b8b5-48e0d9344228/releases/1.0.0/.

Wesselow, M., Stoll-Kleemann, S., 2018. Role-playing games in natural resource management and research: lessons learned from theory and practice. Geogr. J. 184, 298–309. https://doi.org/10.1111/geoj.12248.

Wilensky, U., Rand, W., 2015. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo. The MIT Press.