Interdisciplinary modeling and participatory simulation of forest management to foster adaptation to climate change

Timothée Fouqueray, Julie Latune, Michel Trommetter, Nathalie Frascaria-Lacoste

Interdisciplinary modeling and participatory simulation of forest management to foster adaptation to climate change

Authors: Timothée Fouqueray[a]*, Julie Latune[a], Michel Trommetter[b], Nathalie Frascaria-Lacoste[a]

[a] Université Paris-Saclay, CNRS, AgroParisTech, Ecologie Systématique Evolution, 91405, Orsay, France

[b] GAEL, INRA, CNRS, Grenoble INP, Univ. Grenoble Alpes, 38000, Grenoble, France

* Corresponding author (+33169155662; Université Paris-Sud, Bâtiment 360, 15 rue du doyen André Guinier, Orsay 91405, France)

Email adresses: timothee.fouqueray@universite-paris-saclay.fr, julie.lombard-latune@universite-paris-saclay.fr, michel.trommetter@inrae.fr, nathalie.frascaria-lacoste@agroparistech.fr

Abstract:

The adaptive capacity of forests and foresters to overcome the adverse effects of climate change remains highly uncertain despite intense research efforts. While foresters are often invited "not to put all their eggs in one basket," adaptation strategies to climate change mostly depend on silvicultural diversification. To explore how socioeconomic adaptive tools can complement these technical evolutions in forestry, we designed an interdisciplinary and participatory simulation of forest management combining a role-playing game, ecological models of forest evolution, and a severe climate change scenario. Participants from French natural parks and forest organizations responded positively to its multiple applications. Here, we investigate the technical and timber-focused framing of climate change by forest managers. We also analyze participants' negotiations when attempting to change the simulation rules of forest management. Drawing on this experience, we highlight how establishing a payment system for ecosystem services can reduce financial imbalance driven by climate change.

Highlights:

- Interdisciplinary tool *Foster Forest* explores forest adaptation to climate risks.
- Forest management simulations are positively received by forest organizations.
- Participatory simulations successfully foster unregretful and economic adaptations.
- Economic adaptation involves shunting climate uncertainty about timber incomes.
- Economic adaptation induces commodifying non-provisioning ecosystem services.
- Collective adaptive action is steered by stakeholders with a public interest role.

Keywords: participatory simulation, interdisciplinary, forest management, adaptation, climate change, social-ecological.

Software availability:

Software name: FosterForest_III. First available: 2020. Program size: 2.3MB. Program language: SmallTalk. Developer: Timothée Fouqueray (see contact information in the authors' section). Hardware: PC platforms supporting VisualWorks (VW7.6). Software: Cormas platform, version 2018.5.30 (download from http://cormas.cirad.fr/en/outil/download/). License: Foster Forest is licensed with the French Agency for Program Protection. Freely available at www.fosterforest.fr. ODD+D description: see Appendix A.

1. Introduction

The reality of climate change is now certain, although the magnitude of its spatial and temporal impacts on the environment is not (IPCC, 2021). As one of the most important ecosystems on the planet, forests will face profound long-term changes such as modified species assemblages to an extent that is still unpredictable (García-Valdés et al., 2020; Lindner et al., 2010). In the short to medium term, the productivity of forests in southern and eastern Europe is expected to worsen because of the decreased health of forests caused by rarer cold extremes and more frequent heat waves (Bréda et al., 2006; Ciais et al., 2005; Lindner et al., 2010). The interaction of these hazards and phenological changes with introduced and native pathogens is another matter of concern, with a great potential for damage (Bakys et al., 2009; Futai, 2013). Hence, it is unclear whether forest species will have sufficient adaptive capacity to cope with climate change (Aitken et al., 2008; Corlett and Westcott, 2013). For instance, the ability of tree populations and species to overcome climate change is still being discussed (Alberto et al., 2013). As a result, forest managers are trying to develop complementary adaptation strategies (Keenan, 2015; Millar et al., 2007) to maintain the numerous ecosystem services (ES) provided by forests such as timber production, leisure activities, carbon storage, and water filtering (Brockerhoff et al., 2017). A key feature of robust anthropogenic adaptation is accounting for the uncertainties of climate change: in a highly uncertain context, foresters can favor risk dilution by using different tree species, ages, and silvicultural systems (Kennedy and Koch, 2004; Naumann et al., 2011). Instead of optimizing the performance of a forest stand, this "bet-hedging" approach seeks to minimize ES loss (Spittlehouse and Stewart, 2004).

The issue of climate change is taken seriously in the field of forest sciences, and multifarious research projects aim to develop a series of readily available adaptation options (Bolte et al., 2009; Fouqueray and Frascaria-Lacoste, 2020; Keenan, 2015; Millar et al., 2007) or refine predictive models of forest growth under climate change (Härkönen et al., 2019). To assess the operability of these innovations, researchers can rely on an active network of forest landholders and managers eager to participate in experimental tests, as demonstrated by many studies conducted in France (CNPF, 2016), Europe (Kolström et al., 2011), and the United States (Nagel et al., 2017). However, there is a difference between studies that expand existing knowledge on the potential range of adaptation strategies and those that explore what is currently being undertaken in the field. The available literature on what foresters are actually doing to prepare for climate change is scarce. Based on individual interviews and questionnaires, it shows that field practitioners do not wait for research outcomes to change their management practices (Fouqueray et al., 2020; Kolström et al., 2011; Van Gameren, 2014). It also stresses the emphasis placed on timber production and forestry technical changes such as species replacement or the tree density of forest stands, which is a typical trend in forestry (Dobbertin and Nobis, 2010).

Two conclusions arise from this state of the art. First, the interactions between the different forest stakeholders in the adaptation process have been scarcely examined to date. When adapting, forest managers gear their silvicultural practices toward the provision of one or multiple target ES (Duncker et al., 2012), which can positively or negatively affect the management success of the neighboring stands: for instance, a preference for hunting in one place can threaten the regeneration of trees in another. A forester can also be inspired by management changes made by another forester, or they can develop ideas together that would not have emerged otherwise. Second, several articles stress the value of thinking outside the box and considering non-technical changes as complementary mechanisms (Hallegatte, 2009; Jacobs et al., 2015; Naumann et al., 2011). For instance, as foresters draw most of their financial resources from timber production, they will be at risk of climate change threatening the productivity of trees. To balance their sources of revenue, foresters can look toward insights from other disciplines as opposed to the forest sciences alone. For instance, they can look toward the social and economic sciences to adopt economic tools for timber sales by adding value to timber products through quality labels or turning toward insurance and supply contracts with climate-related clauses, among others. Foresters can also diversify their income by investing in ES other than timber production such as carbon storage contracts (Tronquet et al., 2017).

To the best of our knowledge, no forest management research has addressed the issue of adaptation to climate change with these two questions in mind. Consequently, the objective of this paper is to describe a new method addressing this knowledge gap and to present the results drawn from its application in nine different study cases. The first step was to develop a methodological tool able to do the following: (1) be prospective and integrate foresters' decisions at a regional level, because this is the scale at which most forest public policies are negotiated – at least in France, the country of the study cases (MAAF, 2017); (2) incorporate technical adaptations but artificially limit their effectiveness because of a strong climate change scenario encouraging foresters to develop complementary tools from the organizational or economic sciences; and (3) allow the emergence of spontaneous and/or collective designs for adaptations to climate change in forestry.

With these reasons in mind, we created *Foster Forest*, a participatory simulation combining a computerized agent-based model (ABM) and a role-playing game (RPG) as defined by Barreteau et al. (2001). Participatory simulations and RPGs tend to focus on existing forest issues such as non-temperate ecosystems or the interaction between forestry and other land uses (e.g., Etienne et al., 2008; Étienne, 2003; Fauvelle and Garcia, 2018), instead of adaptation to climate change. However, RPGs are pertinent for the study of adaptation to climate change (Reckien and Eisenack, 2013; van Pelt et al., 2015) and global changes associated with forests (Garcia, 2019). We decided to use the companion modeling (ComMod) approach (Barreteau et al., 2003; Étienne, 2010), a relevant methodology to develop a participatory simulation on forestry in temperate ecosystems. Indeed, it is used for research, training, or negotiation purposes and is particularly useful for encouraging participant understanding and engagement in the management of social-ecological ecosystems (SES) (Bousquet and Le Page, 2004; Voinov et al., 2018). ComMod relies on the involvement of stakeholders to define and develop a model of the SES of interest. Finally, since stakeholders involved in the design of the model do not necessarily participate in the simulation (Hassenforder et al., 2016), participants are invited to embody the different roles integrated in *Foster Forest*. They make management decisions in a simulated hybrid environment that reproduces social, economic, and ecological processes (Becu et al., 2016). Some of these processes can be computerized (most often in an ABM): in the case of *Foster Forest*, this includes indicators of social satisfaction, prices for hunting rights, or forest growth. Lastly, ComMod complies with our methodological requirements, because it can model SES at a regional scale, allow spontaneous changes to emerge in the "rules of the game," and explore scenarios of future forest management. To best apply the interdisciplinary ComMod approach, our research team was comprised of two ecologists, a geographer, and an economist.

In the following sections, we introduce the conceptual framework used to decide modeling choices. We then present the ABM and RPG behind *Foster Forest*'s participatory simulations. We conclude with the description and discussion of the results relating to the nine French study cases. France was chosen as our study area, because its forestry situation is particularly relevant to climate change adaptation: the country has the fourth largest area of forests in Europe (165,000 km^2) (MAAF, 2017). Its legal regulations and public policies are also representative of countries adopting a multifunctional management of forests with the simultaneous provision of timber production, leisure activities, and biodiversity conservation (Légifrance, 2012). The timber industry and forest management provide numerous jobs, whether in private stands (75% of the surface) or in public forests (MAAF, 2017). Thus, adaptation is of great importance and is acknowledged in numerous public policies (MAAF, 2017; ONERC, 2015) and research projects (Fouqueray and Frascaria-Lacoste, 2020).

2. Collective construction of the conceptual model

2.1. A social-ecological framing of stakeholders' interdependencies

The analytical conceptual framework developed by Barnaud et al. (2018) for studying ES, social interdependencies, and collective action in SES inspired the design of *Foster Forest*. ES are at the core of this framework, which stresses the synergetic, antagonistic, or neutral relationships between ES providers and beneficiaries and their intermediaries (Fig. 1). The interdependencies can relate to different ES providers (e.g., private landholders and managers of public forests), ES providers and beneficiaries (e.g., forest managers whose stand regeneration suffers from overgrazing by boars and deer, hunters responsible for avoiding the overpopulation of game animals), and ES beneficiaries (e.g., motorcyclists, hikers). These interdependencies are reshaped by changes in management decisions that modify ES and by new trade-offs between the different interests of forest stakeholders. Intermediaries promoting collective actions such as natural regional parks (NRP) also contribute to the permanent rearrangement of these social relationships.

To apply this framework to *Foster Forest,* we decided that participants would have asymmetrical interdependencies (Becu, 2020). Whereas the information about the forest is freely accessible (land ownership, soil quality, etc.), each player has its own objectives and actions (Fig. 2).

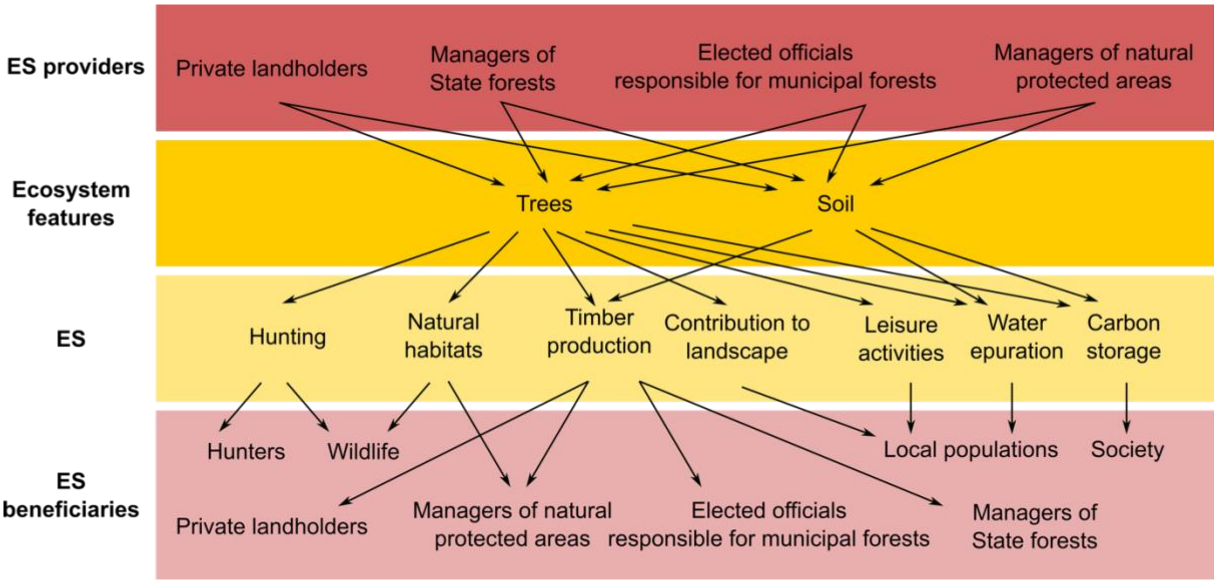


Figure 1. A simplified version of the *Foster Forest* conceptual model. ES: ecosystem services. Forest ES that do not relate to adaptation issues such as erosion control were not included in the model.

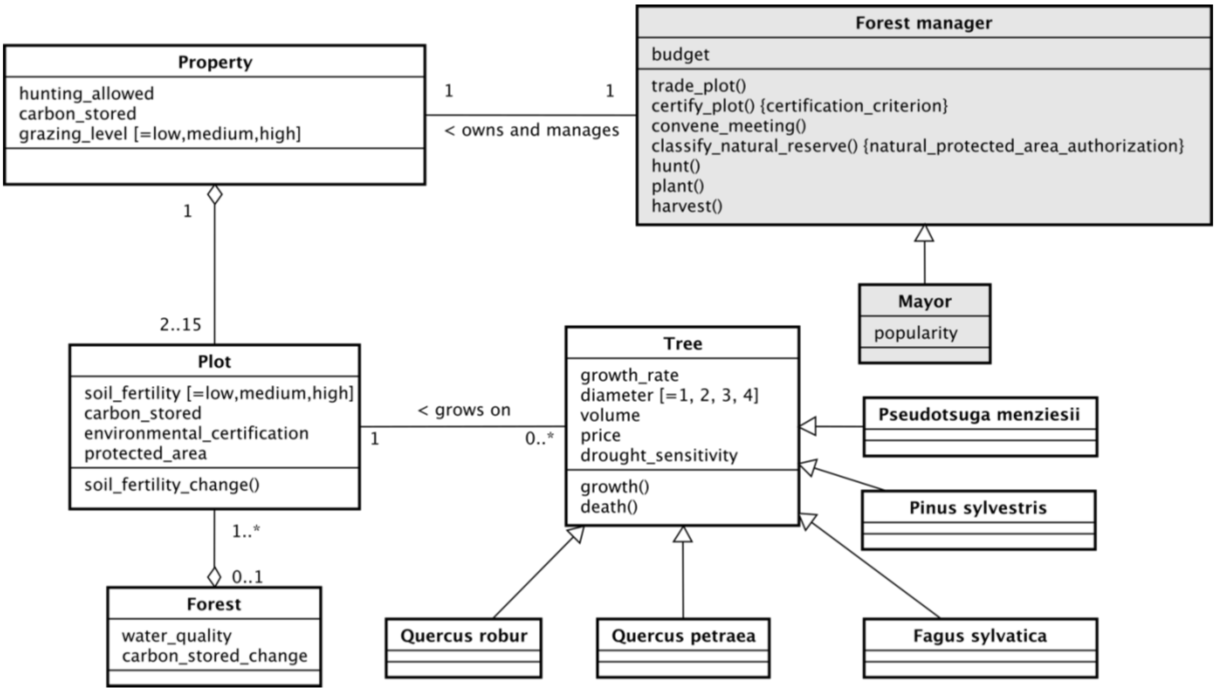


Figure 2. UML overview of the *Foster Forest* agent-based model. Gray: non-autonomous agents controlled by *Foster Forest* participants.

2.2. Building the conceptual model

The conceptual model (Fig. 1) required the reduction of forest management complexity to its minimum features of interest. A major challenge was to balance this reduction with our objectives of studying adaptations to climate change, which potentially affects every single aspect of forestry. Another difficulty was to create an intermediate model of forestry: not too specific to a given region but also not too broad so that foresters could easily connect it to their reality.

Because of our specific requirements, we applied a shortened version of the ComMod approach to build the conceptual model. As we needed a generic tool applicable to any French temperate forest instead of a precise regional case, we did not involve stakeholders during the earliest stages of the modeling process. Instead, we completed a first version of the model using previous analyses of foresters' decision-making (Fouqueray et al., 2020). Then, as a first step, we interviewed different forestry experts to gain complementary insights to develop an improved version. A second step led to the final version of the conceptual model, conceived during a test workshop hosted by the NRP of the "Vosges du Nord," which brought together public and private foresters in September 2018.

The inclusion of forest stakeholders greatly improved the model, for instance, with regard to the exclusion of abrupt disturbance events. Fires, droughts, or windstorms are far from negligible, although cognitive biases increase the chances that they lead to adaptations compared to the incremental impacts of climate change (Morin et al., 2015; Weinstein, 1984). Foresters are used to thinking in the long term, so we tailored *Foster Forest* to progressively integrate the evolution of mean annual temperatures and precipitations among others. It was in this vein that one interviewee suggested discarding disturbance events to focus on "slow variables," an opinion shared by the other participants of the test workshop. We followed his recommendation, which was consistent with feedback from other ComMod researchers that introducing a crisis would restrict the debates to short-term technical discussions among participants. Participants of the game sessions generally agreed with these conceptual choices.

The second step was also valuable in order to legitimate certain biases such as making the participants the ultimate decision-makers of forest management. Intermediary bodies were not included as agents in the model; their influence was only considered in the evolutive processes of objects in the model. For instance, forest cooperatives can modify timber prices, although this effect is encompassed by random variations in timber prices around a fixed mean.

2.3. A model restricted to five providers of ecosystem services

The final conceptual model of *Foster Forest* includes five ES providers. Three are forest managers representative of publicly owned forests: an elected official of a municipality owning communal forests (“mayor”), a National Forests Office manager (“public forester” managing state forests), and a manager of a natural protected area (“protected area manager”). Two private forest landholders (“landowners”) complete the group. However, as it can be difficult to recruit landowners, they can be replaced by a private forest advisor or a public advisor from the Regional Centers for Privately Owned Forests (regional public bodies seeking to increase wood mobilization among private landowners so as to indirectly stimulate the timber industry). During the participatory simulation, foresters play their own role.

In accordance with the conceptual model, each role is attributed certain objectives. The mayor must avoid the deterioration of water quality and promote forestry operations that positively contribute to the esthetic value of the forest landscape. Current regulations in French public forests aim to harvest 50% of tree production, which will certainly increase with the rising demand in forest biomass (Collectif, 2016; Scarlat et al., 2019). In line with this, the public forester must harvest 70% of the volume of the decadal tree production (a figure that the facilitator can adjust depending on the context of the workshop). The area manager must convince the other participants to subscribe to a program for the conservation of old-growth forest in order to reach a total of seven plots at the end of the simulation. She/he must also provide any relevant information likely to favor carbon storage. Like all the other players, the landowners must maintain a balanced budget and avoid the detrimental effects of overgrazing.

A facilitator hosts the participatory simulations by explaining the rules and playing the role of a climate expert or state official to respond to participants’ questions about any climate, forest, or regulatory issue. She/he is accompanied by an observer in charge of noting information (discussions, behaviors, decisions, etc.) relevant to the research question.

The “Overview, Design Concepts, and Details” framework (Müller et al., 2013) summarizes *Foster Forest*’s features in Appendix A to simplify its comparison with other ABM including human decision-making.

3. Agent-based model behind *Foster Forest*

Foster Forest is a hybrid composite simulation (Le Page et al., 2011), which combines features of both ABM and RPG. It is both hybrid and composite because of its combination of autonomous avatars of agents, humans controlling non-autonomous avatars (or their computerized representations), and semi-autonomous agents (humans with limited options of control). Here, we present the ABM on which *Foster Forest* relies.

3.1. Model classes and calibration sources

Foster Forest's ABM includes spatial entities (plots and properties), semi-autonomous social entities (foresters), and physical entities (trees) (Fig. 2). The simulation environment is stylized, which means that the characteristics of each of the classes are proportional to French temperate forests (Le Page and Perrotton, 2017). For instance, the initial distribution of pure or species-mixed forest stands is based on empirical data from the National Forest Inventory (IFN, 2017). Abstract and representative environments were discarded for two reasons. First, we needed a prospective tool to allow for comparisons between different regions in the same legislative and economic context, namely France. Abstract or representative environments could not lead to comparisons of regional social-ecological frameworks (Barreteau et al., 2001). Second, a stylized environment distances participants from the issues that they face on a daily basis and facilitates their reflective behaviors during the participatory simulation (Étienne, 2010).

Forest plots are the basic units of spatial entities. Plots have one parameter for soil fertility and another for carbon storage. Soil fertility, a combination of natural soil fertility and artificial soil compaction, is important for the calculation of tree growth. Updating soil fertility and aboveground carbon storage occurs at the plot scale. Depending on their tree species mixture, plots can be eligible for the old-growth conservation program. Plots are grouped by properties and distributed among foresters according to the mean proportions of the French ownership structure, as taken from the National Forest Inventory (IFN, 2017). Properties are characterized by a level of grazing in order to account for the grazing pressure placed on tree regeneration by boars and deer (not represented in the ABM).

In the ABM, foresters are semi-autonomous social entities: participants control pre-determined actions of the "forest manager" class. Forest managers are characterized by forest ownership and a budget. They can trade forest plots or timber and decide on the intensity of hunting.

The only physical entities of the model are trees. Trees are located on plots and are categorized by species and diameter. The parameters of each species differ in terms of growth rate, wood price, and sensitivity to drought. We retained five different species, namely beech (*Fagus sylvatica*), pedunculate and sessile oaks (*Quercus robur* and *Quercus petraea*), pine

(*Pinus sylvestris*), and Douglas fir (*Pseudotsuga menziesii*), so as to include a range of timber productivities, prices, and drought sensitivities similar to what foresters face in the field. For instance, beech was the most drought-sensitive species, while Douglas fir was the most profitable (Bréda et al., 2006; Direction des Ressources Forestières et al., 2017). Four categories of diameters were chosen to mimic the distinction of wood products used in the timber industry and refine the ecological parameters depending on the development of trees (e.g., young and old trees differ in terms of their survival, growth, and reproduction rates).

Appendices B and C present the parameter choices and data sources for the initial situation.

3.2. Computerized processes and players' actions

In *Foster Forest*, computerized processes calculate the successive stages of the spatial, social, and physical entities. Most function in response to the decisions taken by participants, although some form part of a fixed climatic or economic scenario. This could seem to go against the importance of having uncertain climate change scenarios in *Foster Forest.* However, the climate information given to the participants is very vague and only runs for the ongoing round. As first-time players, the evolution of the climate remains very uncertain from their perspective.

3.2.1. Simulation of forest growth

The survival, reproduction, and growth of trees are simulated at the stand (plot) level and not at the tree level in order to avoid cumulated model errors from the tree to the stand level (Porté and Bartelink, 2002). The inclusion of ecological processes such as asymmetric competition, the increased impact of grazing on seedlings, and so on (Fig. 3) was an important requirement in the selection process of a forest growth model for *Foster Forest*. The level of accuracy and the limitations of the growth model were communicated to participants during an introductory briefing.

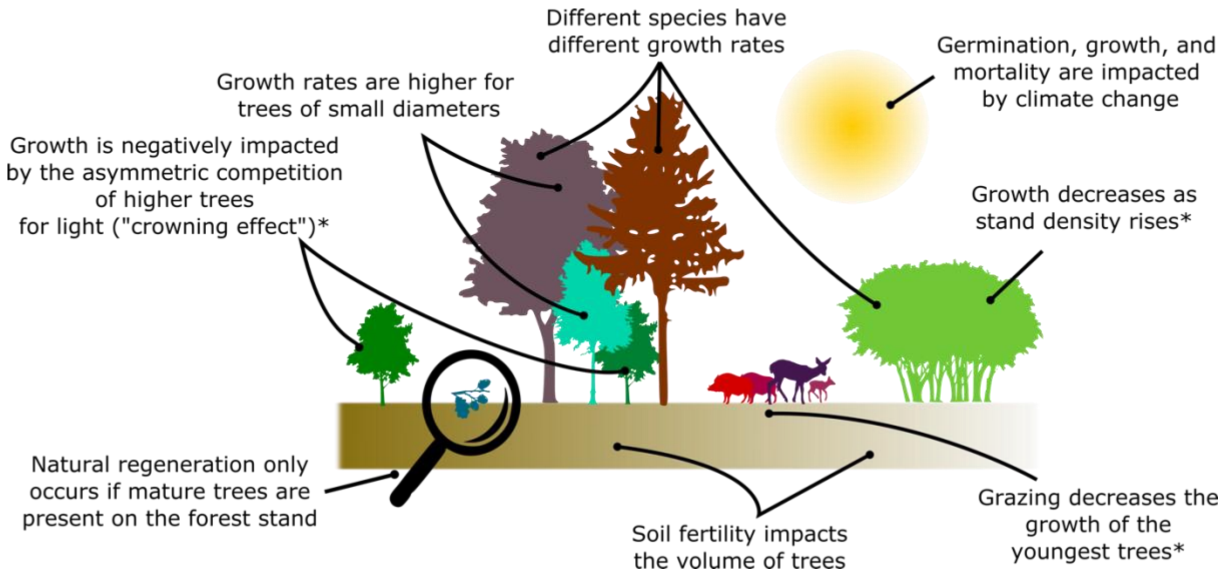


Figure 3. Parameters influencing the growth of trees in *Foster Forest*.

*These parameters are species-specific. For instance, the crowning effect is higher for oaks than for beeches (Appendix B).

The forest growth model used in *Foster Forest*'s ABM is inspired by Kohyama and Takada (2012) as well as Mathias et al. (2015). The growth model, presented in Appendix B, simulates the dynamics of 1 ha of uneven-aged forest stands containing five different tree species of four diameters. Its execution by CORMAS was very rapid, which avoided interruptions during the participatory simulations.

We fixed the computational timestep at 10 years. After discussions with private and public foresters, this was considered to be a plausible balance between the 10-to-20-year duration used in private forests' management plans (mandatory for forest estates larger than 25 ha), the updating of climate parameters (further detailed in section 3 of Appendix B) and economic prices (see Appendix C), and the turnover rate of silvicultural operations in even-aged stands.

3.2.2. Computerizing participants' decisions and their effects on the agent-based model

Attendees can choose between many actions specific to forest management such as tree harvesting or hunting. During a participatory simulation, players have two information sources at their disposal to reach their objectives. First, a personal booklet lists the different silvicultural actions (Fig. 2) and their consequences on social, ecological, and economic indicators (inhabitants' satisfaction; soil fertility, water quality, grazing rates; personal budget). Second, two maps of the simulation environment are projected (Fig. 4). One is projected onto a vertical screen; it shows the 50 plots of the simulation, with a background map of the property boundaries and a forest inventory of each plot's forest (number of trees per hectare, by species and diameter). The second map is displayed horizontally on a table close to the players using an ultra-short throw projector. It is made available at the request of participants to show them any information of interest. For instance, the protected area manager can ask for the location of plots eligible for the conservation program.

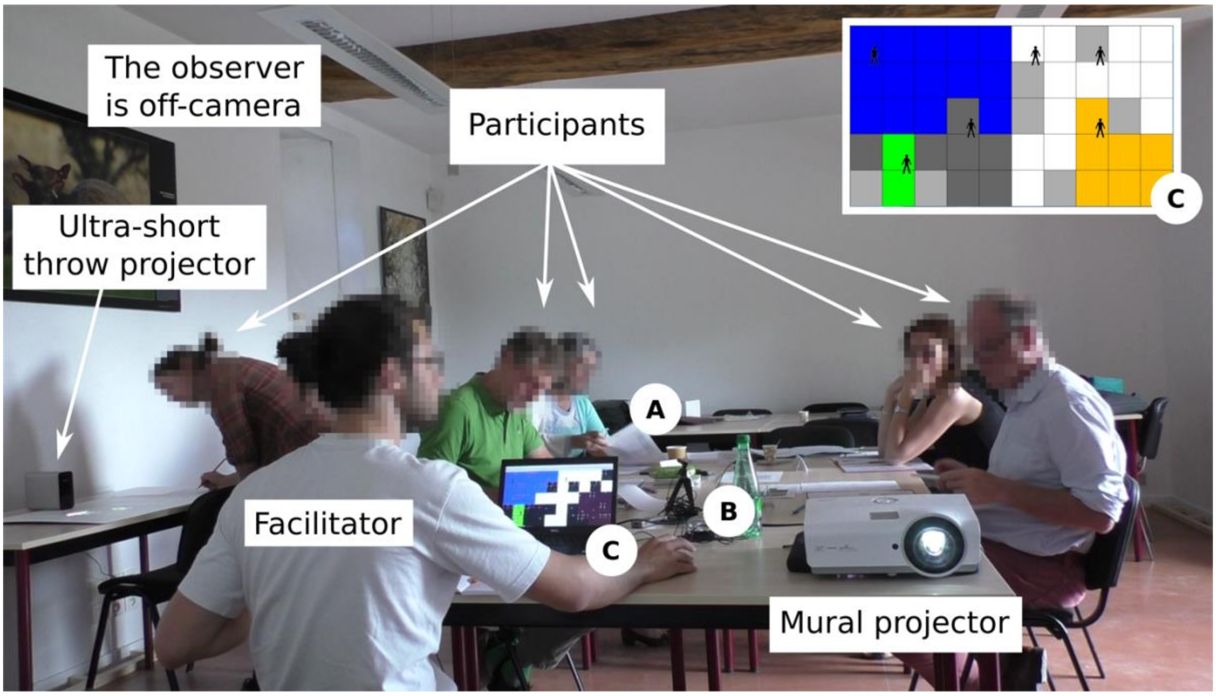


Figure 4. Set-up of a participatory simulation of *Foster Forest*. A: The participant reads the explanatory booklet. B: Sound recording system, supplemented by a video recording system from which the photograph was taken. C: Background map of the simulation with colored properties. This main map is duplicated by a vertical projection onto the wall. Appendix D further details the visual interface.

As soon as they decide on their forest operations, the participants go to the facilitator who implements their decisions on the computer.

Participants first specify their preferred contract for hunting leases, geared toward either hunting (a lower hunting intensity entails a higher presence of game with a higher grazing rate but also a higher lease payment) or timber production (lower lease payment but increased hunting and therefore lower grazing intensity affecting planted and natural seedlings) (Appendix B).

Participants then give instructions for the forest operations to take place on every plot of the estate that they possess or manage: voluntary or paid participation in the fake "PFSC" certification system – an *ad hoc* mixture of the Program for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) –, number of trees harvested (detailed by species and diameters), slash removal, and plantation if needed. The foresters' budgets change directly in line with the implemented silvicultural actions in order to reflect the costs (workforce wages, nursery seedlings, skidding, taxes, etc.) and benefits (timber revenues) of the forestry operations. Ecological indicators also evolve in relation to the participants' silvicultural choices: soil fertility decreases in the case of slash removal, clearcutting of an entire plot, or softwood planting, although it increases when nothing happens (Appendix C). Slash removal also lessens the belowground carbon stock (Appendix C). Water quality, measured at the whole forest scale, depends on the mean soil fertility, the proportion of coniferous species, and the number of clearcut plots (Appendix C).

In a last step, participants state their potential interest in selling or buying forest plots or in engaging in the old-growth conservation program. Land transactions occur at the end of the round, once all participants have computerized their decisions. The conservation program, which is operated by the protected area manager, targets the protection of old-growth trees. Conservation contracts last for 30 years, and during this time, contractors engage not to cut the oldest trees. In compensation, they benefit from a payment proportional to the financial shortfall.

Appendix D displays two visual interfaces. The first is used to implement players' decisions during a round. The second presents the evolution of social, ecological, and economic indicators between two rounds.

3.3. Testing the calibration and scenarios

It was extremely complex to configure the calibration, scenarios, and rules to obtain a participatory simulation that was plausible, playable, and open to the spontaneous and novel ideas of participants. Therefore, the parameters and scenarios used in *Foster Forest* were tested during two preliminary sessions held with students and researchers prior to the nine study cases. The two test sessions brought about three major changes.

First, they highlighted the importance of an exhaustive introductory brief to justify the simplifications made to the conceptual model. For instance, the facilitator subsequently stated that land prices would not evolve and that the mayor's role would not be affected by municipal elections that would "occur" during a simulation.

Second, the test sessions emphasized the usefulness of pre-coded functions in the ABM, which were not communicated to participants, so as to facilitate a *free-play* mode permitting experimentation (Becu, 2020). As one of the objectives of *Foster Forest* is to encourage foresters to propose organizational or economic changes in their forest management, it helped the facilitator to have pre-coded, ready-to-use processes at his disposal to implement the players' ideas. However, these were only revealed if the foresters explicitly asked for them so as not to impede any spontaneous innovations that they could generate. Such functions included the calculation of carbon flows in every participant's property or the possibility for protected area managers to create a subsidy system to reward sustainable forestry practices.

Third, feedback also contributed to improving the graphical display of the available information sources as well as the spatial and temporal configurations of the simulations.

4. *Foster Forest*, a participatory simulation with a role-playing game

4.1. Temporal organization of the participatory simulations

The participatory simulation follows five steps: (1) a pre-simulation questionnaire; (2) a briefing; (3) different rounds of the simulation; (4) a post-simulation questionnaire; and (5) a collective debriefing.

The pre-simulation questionnaire aims to gauge the participant's sensitivity to climate change (e.g., if they had already experienced a climate catastrophe) and the multiple issues affecting forest management (e.g., the most important forest ES issues). The questionnaire also includes a "participation contract," which details the context of the study and its funding (public research, with no declared conflict of interest). By signing the contract, the players acknowledge that their participation is not binding. They give their consent for the authors to use their anonymized image and voice for the purpose of the research project.

During the introductory brief, the facilitator presents the different roles and their objectives, the information sources (booklets, mural and horizontal projections, and economic and climatic information posted on a wall), the list of possible actions, and the implementation process in the computer.

The simulation only begins after completing these two initial steps. It consists of three to five similar steps, each corresponding to a 10-year period (step 1: 2020-2029, step 2: 2030-2039, etc.). Each step starts with announcements concerning decadal projections for climate change as well as timber and carbon prices. The players can then freely talk with each other and approach the facilitator at any time to implement their forest management decisions, with no predefined order for taking turns. A ringtone announces the end of the action period and the launch of the computerized updating of the spatial, social, and physical entities. At this point, the facilitator spends 10 min providing a collective overview of the forest, property, and stand parameters (see Fig. 2), and communicates the climate record of the last decade. The end of a step is also the appropriate time for participants to ask for the organization of a meeting on any issue of importance to them – for instance, a meeting was once requested by a mayor to elaborate a collective strategy to reinforce the social acceptability of tree removal. Overall, each step lasts 20 to 40 min, except for the first one (1 h) to account for the learning phase.

The post-simulation questionnaire aims to compare the strategies adopted during the game with the real-world choices operated by the foresters. It also asks participants what they learnt from the workshop and includes time for the suggestion of improvements.

Finally, at least one hour is dedicated to collective debriefing. Debriefing is crucial, because it allows participants to provide feedback on the conceptual model and its implementation, which enables its validation and further improvements (Guyot and Honiden, 2006). The first part of the debriefing is inspired by the "most significant change" method (Perez et al., 2010): participants are successively encouraged to express one or two changes considered to be of particular importance to the simulation. This is experienced as a sort of emotional relief for the speaker, while it reminds other players what happened and provides insights into the speaker's priorities for subsequent analysis. This is also useful for the facilitator during the second part of the debriefing, which involves a roundtable discussion focusing on three topics. First, we ask participants how they tried to reach their objectives and what obstacles they encountered. Second, we return to the thought-provoking elements of the discussions or the spontaneous collective behavior relating to the issue of climate change adaptation. Third, we steer the discussion toward participants' reactions to the strong climate scenario, which often ended in a general discussion about the limitations and merits of participatory simulations.

4.2. Spatial organization of the participatory simulations

Seat distribution is unchanged throughout the simulations in order to facilitate the subsequent video comparison of strategies developed by different participants with the same role. The spatial configuration of seats also mimics real-world patterns of interactions between participants. For instance, it is legally embedded that the National Forests Office must provide technical assistance to elected officials of municipalities that own communal forests; hence, the public forester and the mayor are always placed next to each other.

When seated, all participants can see the vertical projection of the main map. However, they must move to see the horizontal screen, most often placed on a smaller support isolated from the central table, while the economic prices are pinned on a wall. This enables us to refine our observations regarding the information searched by the participants (who they are, when they need the information, etc.). Participants can also move throughout the simulation space to communicate with each other or with the facilitator. The computer on which the facilitator inputs the players' decisions is located on one side of the room. The observer does not interact with the participants.

To allow for the later analysis of the workshops, every simulation is recorded using a video camera and two voice recorders placed on the main table.

5. Results from nine study cases

5.1. Study cases analysis

5.1.1. Presentation of the study cases

Nine workshops, conducted following the methods described in section 3, occurred between May and July 2019. In chronological order, the simulations took place in the NRP of the "Vosges du Nord," in Rouen (Normandy, two sessions), in the NRP of the "Pyrénées Ariégeoises" (two sessions), in the NRP of the "Perche," in the NRP of the "Boucles de Seine Normande," in Louviers (Normandy), and in the NRP of the "Volcans d'Auvergne." The same facilitator-observer duo was present for the nine study cases.

Natural regional parks and the regional community forest federation of Normandy were essential partners to recruit players and host the simulations. Workshops were programmed to last for 4 hours in order to facilitate the recruitment of participants who often have busy schedules. Organizers' knowledge of local foresters and their involvement in the organization of the simulations greatly increased the legitimacy of the research team in the eyes of participants. Their interest in the tool was motivated by its potential use as a support for collective decision-making or awareness-raising about climate change (Flood et al., 2018). This was yet another demonstration of the joint use of ComMod approaches for research, training, or negotiation purposes (Barreteau et al., 2003).

5.1.2. Methodological approach

The analysis was based on the observer's notes, the questionnaires, and the audio and video content collected during the workshops. Any moments of interest (e.g., discussions, negotiations) identified in the simulations were transcribed, as were all the debriefing sessions. Audio recordings and written transcriptions were analyzed using Sonal, an encoder software that conducts audio-textual synchronization (Nicolas, 2013). Sonal allows for thematic and statistic discourse studies such as topic occurrences and co-occurrences (e.g., “climate change” and/or “timber production”). For our analysis, we coded the informative segments of each participatory simulation with thematic tags. These tags related to the components of the conceptual framework (ES providers and beneficiaries, ecosystem features, ES, as detailed in Fig. 1), climate change features, and *Foster Forest* as a participatory simulation (Table 1).

Table 1. Analytical focus of the participatory simulations. The list is not exhaustive.

Analytical focus	Categories	Examples
Conceptual model	Providers of ecosystem services	National Forests Office Municipality owning communal forests Managers of natural protected areas Forest landholders
	Beneficiaries of ecosystem services	Same as the providers Local populations
	Ecosystem services	Timber production Water filtering Hunting Hiking, bike riding, etc. Carbon storage
	Interaction between ES stakeholders	Intermediary bodies (natural regional parks, etc.) Contractualization, public policies, collective action
Adaptive change in forest management	Forest management approach, *sensu* Duncker et al. (2012)	Free evolution Low to intense interventions Short term/long term
	Adaptation implementation	Effectiveness of the adaptation Cause of adaptation (incremental changes, climate projections, etc.)
Participatory simulation	Structuration and biases of the model	Climate forcing Hidden functions encoded in the ABM Individual/collective gaming
	Suggested improvements	Ergonomics Model reductionism Calibration

5.2. Lessons learnt from the study cases

5.2.1. Climate change adaptation: Technical, timber-focused, and of secondary importance

Despite the strong emphasis placed on the impacts of climate change through the announcements of decadal climate projections, participants' two primary matters of concern were the balance between forest regeneration and game animals, and the local population's perception of forest operations. Public and private foresters regretted the many complaints made by forest neighbors about the modifications to forest scenery . Consistent throughout the study cases, this feeling of social pressure was most prominent in the "Volcans d'Auvergne" NRP, a very touristic region listed as World Heritage (UNESCO, 2019). The issue was also of importance in the "Boucles de Seine Normande" session, where players spontaneously called a meeting to create an awareness program, which the facilitator then directly encoded into the program by decreasing inhabitants' satisfaction threshold.

In comparison to these two issues, participants' verbal reactions to climate change were lesser than expected, and overall, they focused on the low rate of natural regeneration. We assume that this originates from the climate scenario, centered on incremental changes (less prone to trigger reactions) and not on strong climate events – by contrast, participants spoke at length about the disease outbreaks and windthrows that they had experienced, but this was not reflected in the simulations. Nevertheless, in all the participatory simulations, adaptive changes were notable in participants' forest management decisions. In coherence with the findings outlined in the introduction, these changes focused on species replacement and stand density in order to maintain timber production. The essence of this belief in the potency of technical developments is epitomized as the search for "the right tree at the right place, even in future conditions," as repeated in seven different workshops. Its best illustration is the quest for a turnkey solution: private foresters turn to public foresters to ask for "ready-to-plant" species; public foresters turn to foreign experiences for feedback or to the facilitator to "call the national scientific research center" in order to find drought-resistant tree species; and the facilitator aims to foster non-technical adaptations to climate change.

The search for adapted species was frequently shared by both public and private foresters, but some foresters considered that achieving such outcomes would take decades and that monospecific stands would not be resilient to parasite outbreaks. Hence, they favored risk-dilution through species mixtures. Even though this adaptation strategy was tailored to the stand scale, it was tree-centered, as virtually no forester spoke of forest fauna, flora, or fungi – the only mention of soil fungi was made by a naturalist not trained in forestry.

During the debriefing sessions, participants' emphasis on their way of playing "like in the real world" and the similarity between our findings and insights from field studies (Fouqueray et al., 2020; Kolström et al., 2011; Van Gameren, 2014) stress the relevance of the subsequent analyses for real, non-game situations.

5.2.2. Socio-economic changes in the provision of ecosystem services

While the abovementioned adaptations were common to all workshops, innovative approaches to the conceptual framework of *Foster Forest* emanated from the study areas of Rouen, the "Pyrénées Ariégeoises," and the "Perche." The changes stemmed from the observation that foresters' revenue sources mainly derive from two ES, namely timber production and hunting, which are both threatened by climate change. Indeed, the climatic scenarios introduced considerable uncertainty in terms of the ability of these ES to balance foresters' budgets. In response, participants developed a system of payment for ecosystem services (PES) to attain financial equilibrium through other ES (in all three study areas, this related to carbon storage). As explained by the "Perche" private forest advisor, "I relied on [carbon] contracts to diversify my income and try not to be too dependent on timber prices."

Interestingly, PES were chiefly instigated by participants who were protected area managers but not professional foresters in real life. Based on the debriefings and their questionnaire responses, we may argue that they were inspired by PES pilot projects conducted in French regions, which they had learnt about from forestry newsletters and professional meetings. Collective negotiations addressed three of the four potential flaws of carbon contracts (i.e., heterogeneity of stand conditions, uncertainty of storage due to stochastic weather conditions, additionality of the project, but not the permanence of carbon storage) (Gren and Aklilu, 2016). Heterogeneity and uncertainty were addressed by designing financial incentives with an obligation of means but not of outcomes – most often, remuneration for species mixtures and irregular shelterwood forest management. As a consequence, permanence was not considered in the contracts, because the financial compensation was linked to the duration of the change in forest management and not to the duration of carbon storage. Additionality was evaluated on a case-by-case basis through discussions between protected area managers who oversaw payments for carbon storage and candidates for the contracts.

In the three workshops, the design of the payment for carbon storage allowed us to clearly distinguish between ES providers. Some private foresters adopted an economic approach by switching from being an ES provider to an ES beneficiary: “The day that I’m paid 50€ per hectare annually, I will plant beeches, hazel trees, and even banana trees if you want me to!” Alternatively, the rest of the private foresters relied on carbon contracts as transitional funding to adapt their forest stands to climate change, for instance, by planting drought-resistant species. Mayors and public managers regretted that carbon contracts primarily targeted private landholders, a choice that the protected area managers justified by the importance of private forests (put together, fragmented private plots represent 75% of forest surfaces in France and also in the model). Mayors and public managers stated their preference for large-scale collective planning of forest management. For spatial scales, they suggested the common management of hunting or water quality. For temporal scales, protected area managers relied on carbon contracts as a stepping stone to make forest stands eligible for a conservation program to establish a network of old-growth trees. During the debriefings, two protected area managers stressed the long-term effect of carbon or conservation contracts. In their eyes, even an unsuccessful contract negotiation provides an opportunity, because it raises owners’ awareness about conservation issues.

Spontaneous rule changes aimed at adapting to the scenario’s uncertainties mostly related to PSE. Non-economic narratives exist to provide complementary adaptive tools (Röling and Maarleveld, 1999), but they did not lead to any evolution in the roles of ES providers and beneficiaries, or their interactions. A first lever of change that was discussed was raising awareness about climate change, as acknowledged by private foresters: “The ideal thing is to apply [the clauses of the contract] but without a contract.” Legal tools were another lever of change. The recent possibility for any private landowner to engage in conservation easements (Légifrance, 2016) was briefly discussed but only on one occasion.

5.2.3. Participants’ feedback on *Foster Forest*

Feedback was gathered from the debriefing sessions and the post-simulation questionnaires. Overall, participants appreciated the workshops and validated the conceptual model. Despite lengthy debates on soil, growth, and the calibration of climate parameters, they found the reductionist level to be appropriate: “It’s not just a game with fancy hypotheses, it’s quite realistic and corresponds to reality.” They enjoyed the hidden functions and the facilitator’s ability to dig into the source code when required, for instance, to incorporate the abovementioned awareness program (section 5.2.1.).

They also proved that strategical choices are not predetermined. Despite using the same tool (conservation program), protected area managers adopted different strategies in the study cases.

Some of them initially negotiated conservation contracts with private owners, because they considered that they would be more responsive to the economic argument, while others engaged in discussions with public foresters, as they managed larger forests. We observed a third strategy, with managers applying the conservation program to themselves in order to receive financial income. The revenues were subsequently reinjected into the acquisition of forest plots for new conservation programs.

Most of the improvement requests related to the implementation of the ABM and RPG. Some of the biases voluntarily introduced into the simulations were relevant (e.g., spatial configuration of participants' seats). However, participants found that other biases interfered with the simulations such as the large amount of technical information in the introductory booklets, which aimed at reproducing the asymmetrical understanding of forest functioning, since professional foresters, unlike mayors and some private owners, are used to dealing with technical information. However, one mayor summed up the situation: "We're not experts!" By contrast, this technical bias highlighted the importance of sensory perception for forest management. A forest manager stated that graphical projections were "very mathematical, with colors and figures. I was very perturbed at the beginning, as I don't see forests in this way." Despite some complaints, this validated our use of a stylized environment to spatially represent forests as an assemblage of multifunctional space, a way to stimulate innovative and integrative solutions (Barnaud et al., 2013). Participants partially explained their lack of reaction to climate announcements by the absence of pictures or drawings exemplifying abrupt climate change, a deliberate choice made in order to focus on slow-pace climate change. Drawing on participants' suggestions for improvement, we introduced a forest fire event in a second educational version of the game. To date, however, we did not observe significant changes to the adaptive paths taken between the two versions of *Foster Forest*.

The sessions demonstrated the importance of collective discussions to open up perspectives on the incorporation of climate change in forest management. "We need everybody to face up to this challenge," said a Pyrenean landowner, a conclusion that is consistent with similar findings on environmental issues (e.g., Redpath et al., 2018). Most importantly, the simulations emphasized the prominent role accorded to the intermediaries in designing and promoting collective adaptation to climate change. In *Foster Forest*, the rearrangement of the relationships between ES providers and beneficiaries was always guided by protected area managers and mayors. From a reflective point of view, the organization of collective workshops in the "real world" has also been endorsed by federations of community forests and natural regional parks, as detailed by Bertrand and Fouqueray (2017).

6. Conclusion

Through an interdisciplinary participatory simulation, this paper aims to address the shortcomings in the existing literature regarding the design of diversified, quickly deployable adaptations to climate change in forestry. In *Foster Forest*, forest stakeholders interact with each other in participatory simulations combining a role-playing game and an agent-based model in order to achieve multifunctional objectives of forest management. To overcome the adverse effects of not knowing the climatic and economic scenarios, they can rely on a fixed set of technical tools with limited effectiveness and/or develop collective forms of socio-economic action based on their discussions.

A challenging achievement in the design process was to find an appropriate balance between the reductionism of the conceptual model and its implementation in the ABM and RPG so as to allow players to act on any ES that they would find of interest. As shown by the spontaneous development of game changes in four workshops, this balance was achieved. The ability to experimentally test changes in forest management, with no real risk of financial or temporal loss, is one of the most appreciated features of *Foster Forest* and ComMod approaches in general (Étienne, 2010).

Our findings pave the way for further investigations, especially in terms of the role of participation-based learning. Because of the uncertain nature of climate change, learning by trial and error is not feasible. Participatory simulations can compensate the impossibility of "learning by doing" by means of learning by simulating (Barreteau et al., 2001). We now aim to monitor whether *Foster Forest*'s participants developed other kinds of learning after contributing to such a serious game (i.e., normative, relational, or cognitive learning, as reported in den Haan and van der Voort, 2018). It is worth investigating if simulation-based learning will have tangible effects on participants' forest management, especially since the organizers from the federations of community forests and some natural regional parks stated that they have gained experience in the use of participatory simulations. Their willingness to collaboratively enlarge their toolbox for adaptation has come true, as we developed a simpler and more comprehensive version of *Foster Forest* to foster collective responses of forest management under a changing climate, now available at www.fosterforest.fr.

Acknowledgements: The authors are specifically grateful to Émile Huguet for his calibration assistance; to Bruno Bonté for sharing his knowledge on the forest growth model; to Pierre Bommel for his advice in using CORMAS; to the members of the French National Federation of Forest Communities (FNCOFOR), France Nature Environnement, and the French Union of Forest Cooperatives for discussing the modeling choices; to Véronique Souchère, Géraldine Abbrami, Mélaine Aucante, Sarah Loudin, and Ambroise de Montbel for their constructive criticism of the conceptual model; and to all the participants of the test sessions. The authors especially thank Laure Ferrier, Éric Hincelin, Élodie Roulier, Luc Bélenguier, Jean-Claude Génot, Caroline Salomon, Thierry Mougey, and Pierre Paccard who made the regional workshops possible and the many participants of the game sessions without whom nothing would have been possible. Author contributions: T.F designed the research and coded the model; T.F. and J.L. performed the research; T.F. and J.L. analyzed the data; T.F. wrote the paper; and M.T. and N.F.-L. made additional contributions and edited the manuscript.

References

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S., 2008. Adaptation, migration or extirpation: Climate change outcomes for tree populations. Evol. Appl. 1, 95–111. https://doi.org/10.1111/j.1752-4571.2007.00013.x

Alberto, F.J., Aitken, S.N., Alía, R., González-Martínez, S.C., Hänninen, H., Kremer, A., Lefèvre, F., Lenormand, T., Yeaman, S., Whetten, R., Savolainen, O., 2013. Potential for evolutionary responses to climate change - evidence from tree populations. Glob. Change Biol. 19, 1645–1661. https://doi.org/10.1111/gcb.12181

Bakys, R., Vasaitis, R., Barklund, P., Ihrmark, K., Stenlid, J., 2009. Investigations concerning the role of Chalara fraxinea in declining Fraxinus excelsior. Plant Pathol. 58, 284–292. https://doi.org/10.1111/j.1365-3059.2008.01977.x

Barnaud, C., Corbera, E., Muradian, R., Salliou, N., Sirami, C., Vialatte, A., Choisis, J.-P., Dendoncker, N., Mathevet, R., Moreau, C., 2018. Ecosystem services, social interdependencies, and collective action: a conceptual framework. Ecol. Soc. 23.

Barnaud, C., Le Page, C., Dumrongrojwatthana, P., Trébuil, G., 2013. Spatial representations are not neutral: Lessons from a participatory agent-based modelling process in a land-use conflict. Environ. Model. Softw., Thematic Issue on Spatial Agent-Based Models for Socio-Ecological Systems 45, 150–159. https://doi.org/10.1016/j.envsoft.2011.11.016

Barreteau, O., Antona, M., d'Aquino, P., Aubert, S., Boissau, S., Bousquet, F., Daré, W., Etienne, M., Le Page, C., Mathevet, R., Trébuil, G., Weber, J., 2003. Our Companion Modelling Approach. J. Artif. Soc. Soc. Simul. 6.

Barreteau, O., Bousquet, F., Attonaty, J.-M., 2001. Role-playing games for opening the black box of multi-agent systems: method and lessons of its application to Senegal River 4.

Becu, N., 2020. Les courants d'influence et la pratique de la simulation participative: contours, design et contributions aux changements sociétaux et organisationnels dans les territoires. Rochelle Univ. 270.

Becu, N., Bommel, P., Page, C.L., Bousquet, F., 2016. Participatory simulation and learning process: technology matters! Int. Congr. Environ. Model. Softw.

Bertrand, F., Fouqueray, T., 2017. Un Parc Naturel Régional en apprentissage : enseignements d'une démarche d'adaptation aux changements climatiques des actions en faveur de la biodiversité. Norois Environ. Aménage. Société 47–61. https://doi.org/10.4000/norois.6224

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.-J., Schall, P., Spathelf, P., Rock, J., 2009. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scand. J. For. Res. 24, 473–482. https://doi.org/10.1080/02827580903418224

Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecol. Model. 176, 313–332. https://doi.org/10.1016/j.ecolmodel.2004.01.011

Bréda, N., Huc, R., Granier, A., Dreyer, E., 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Ann. For. Sci. 63, 625–644. https://doi.org/10.1051/forest:2006042

Brockerhoff, E.G., Barbaro, L., Castagneyrol, B., Forrester, D.I., Gardiner, B., González-Olabarria, J.R., Lyver, P.O., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I.D., van der Plas, F., Jactel, H., 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers. Conserv. 26, 3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., Noblet, N.D., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533. https://doi.org/10.1038/nature03972

CNPF, 2016. Pôle expérimentations [WWW Document]. Cent. Natl. Propr. For. URL https://www.cnpf.fr/n/pole-experimentations/n:242 (accessed 9.8.19).

Collectif, 2016. La forêt et le bois en 100 questions.

Corlett, R.T., Westcott, D.A., 2013. Will plant movements keep up with climate change? Trends Ecol. Evol. 28, 482–488. https://doi.org/10.1016/j.tree.2013.04.003

den Haan, R.-J., van der Voort, M., 2018. On Evaluating Social Learning Outcomes of Serious Games to Collaboratively Address Sustainability Problems: A Literature Review. Sustainability 10, 4529. https://doi.org/10.3390/su10124529

Direction des Ressources Forestières, Gembloux Agro-Bio Tech, Gestion des Ressources forestières (Université de Liège), Earth and Life Institute, Environmental Sciences (Université Catholique de Louvain), Forêt Wallonne, 2017. Fichier écologique des essences [WWW Document]. URL https://fichierecologique.be/#!/ (accessed 9.29.19).

Dobbertin, M.K., Nobis, M.P., 2010. Exploring research issues in selected forest journals 1979–2008. Ann. For. Sci. 67, 800–800. https://doi.org/10.1051/forest/2010052

Duncker, P.S., Barreiro, S.M., Hengeveld, G.M., Lind, T., Mason, W.L., Ambrozy, S., Spiecker, H., 2012. Classification of Forest Management Approaches: A New Conceptual Framework and Its Applicability to European Forestry. Ecol. Soc. 17, art51. https://doi.org/10.5751/ES-05262-170451

Étienne, M., 2010. La modélisation d'accompagnement: Une démarche participative en appui au développement durable, Quae. ed.

Étienne, M., 2003. SYLVOPAST: a multiple target role-playing game to assess negotiation processes in sylvopastoral management planning. J. Artif. Soc. Soc. Simul. 6.

Etienne, M., Bourgeois, M., Souchère, V., 2008. Participatory modelling of fire prevention and urbanisation in southern France: from coconstructing to playing with the model. Int. Congr. Environ. Model. Softw.

Fauvelle, É., Garcia, C., 2018. AgriForEst : un jeu pour élaborer des scénarios sur un terroir villageois d'Afrique Centrale. VertigO - Rev. Électronique En Sci. Environ. https://doi.org/10.4000/vertigo.23245

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

Fouqueray, T., Charpentier, A., Trommetter, M., Frascaria-Lacoste, N., 2020. The calm before the storm: How climate change drives forestry evolutions. For. Ecol. Manag. 460, 117880. https://doi.org/10.1016/j.foreco.2020.117880

Fouqueray, T., Frascaria-Lacoste, N., 2020. Social sciences have so much more to bring to climate studies in forest research: a French case study. Ann. For. Sci. 77, 81. https://doi.org/10.1007/s13595-020-00989-3

Futai, K., 2013. Pine Wood Nematode, Bursaphelenchus xylophilus. Annu. Rev. Phytopathol. 51, 61–83. https://doi.org/10.1146/annurev-phyto-081211-172910

Garcia, C., 2019. Could play be a game-changer for the world's forests? [WWW Document]. World Econ. Forum. URL https://www.weforum.org/agenda/2019/05/could-games-solve-the-worlds-deforestation-crisis/ (accessed 5.15.19).

García-Valdés, R., Estrada, A., Early, R., Lehsten, V., Morin, X., 2020. Climate change impacts on long-term forest productivity might be driven by species turnover rather than by changes in tree growth. Glob. Ecol. Biogeogr. 29, 1360–1372. https://doi.org/10.1111/geb.13112

Gren, I.-M., Aklilu, A.Z., 2016. Policy design for forest carbon sequestration: A review of the literature. For. Policy Econ. 70, 128–136. https://doi.org/10.1016/j.forpol.2016.06.008

Guyot, P., Honiden, S., 2006. Agent-Based Participatory Simulations: Merging Multi-Agent Systems and Role-Playing Games. J. Artif. Soc. Soc. Simul. 9, 15.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Glob. Environ. Change 19, 240–247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

Härkönen, S., Neumann, M., Mues, V., Berninger, F., Bronisz, K., Cardellini, G., Chirici, G., Hasenauer, H., Koehl, M., Lang, M., Merganicova, K., Mohren, F., Moiseyev, A., Moreno, A., Mura, M., Muys, B., Olschofsky, K., Del Perugia, B., Rørstad, P.K., Solberg, B., Thivolle-Cazat, A., Trotsiuk, V., Mäkelä, A., 2019. A climate-sensitive forest model for assessing impacts of forest management in Europe. Environ. Model. Softw. 115, 128–143. https://doi.org/10.1016/j.envsoft.2019.02.009

Hassenforder, E., Pittock, J., Barreteau, O., Daniell, K.A., Ferrand, N., 2016. The MEPPP Framework: A Framework for Monitoring and Evaluating Participatory Planning Processes. Environ. Manage. 57, 79–96. https://doi.org/10.1007/s00267-015-0599-5

IFN, 2017. Inventaire Forestier National [WWW Document]. URL http://inventaire-forestier.ign.fr/ (accessed 12.18.17).

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jacobs, B., Nelson, R., Kuruppu, N., Leith, P., 2015. An adaptive capacity guide book: Assessing, building and evaluating the capacity of communities to adapt in a changing climate. South. Slopes Clim. Change Adapt. Res. Partnersh. SCARP Univ. Technol. Syd. Univ. Tasman. Hobart Tasman. ISBN 9781862958272.

Keenan, R.J., 2015. Climate change impacts and adaptation in forest management: a review. Ann. For. Sci. 72, 145–167. https://doi.org/10.1007/s13595-014-0446-5

Kennedy, J.J., Koch, N.E., 2004. Viewing and managing natural resources as human-ecosystem relationships. For. Policy Econ. 6, 497–504. https://doi.org/10.1016/j.forpol.2004.01.002

Kohyama, T.S., Takada, T., 2012. One-sided competition for light promotes coexistence of forest trees that share the same adult height. J. Ecol. 100, 1501–1511. https://doi.org/10.1111/j.1365-2745.2012.02029.x

Kolström, M., Lindner, M., Vilén, T., Maroschek, M., Seidl, R., Lexer, M.J., Netherer, S., Kremer, A., Delzon, S., Barbati, A., Marchetti, M., Corona, P., 2011. Reviewing the Science and Implementation of Climate Change Adaptation Measures in European Forestry. Forests 2, 961–982. https://doi.org/10.3390/f2040961

Le Page, C., Abrami, G., Barreteau, O., Becu, N., Bommel, P., Botta, A., Dray, A., 2011. Models for sharing representations, in: Companion Modeling. A Participatory Approach to Support Sustainable Development. Michel Étienne, pp. 69–96.

Le Page, C., Perrotton, A., 2017. KILT: A Modelling Approach Based on Participatory Agent-Based Simulation of Stylized Socio-Ecosystems to Stimulate Social Learning with Local Stakeholders, in: Sukthankar, G., Rodriguez-Aguilar, J.A. (Eds.), Autonomous Agents and Multiagent Systems. Springer International Publishing, Cham, pp. 31–44. https://doi.org/10.1007/978-3-319-71679-4_3

Légifrance, 2016. Code de l’environnement - Article L132-3, Code de l’environnement.

Légifrance, 2012. Code forestier (nouveau) | Orientations générales [WWW Document]. URL (accessed 8.30.19).

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manag. 259, 698–709. https://doi.org/10.1016/j.foreco.2009.09.023

MAAF, 2017. Programme National de la Forêt et du Bois 2016-2026. Ministère de l’Agriculture, de l’Agroalimentaire et de la Forêt, Paris.

Mathias, J.-D., Bonté, B., Cordonnier, T., de Morogues, F., 2015. Using the Viability Theory to Assess the Flexibility of Forest Managers Under Ecological Intensification. Environ. Manage. 56, 1170–1183. https://doi.org/10.1007/s00267-015-0555-4

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17, 2145–2151.

Morin, M.B., Kneeshaw, D., Doyon, F., Le Goff, H., Bernier, P., Yelle, V., Blondlot, A., Houle, D., 2015. Climate change and the forest sector: Perception of principal impacts and of potential options for adaptation. For. Chron. 91, 395–406.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environ. Model. Softw. 48, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003

Nagel, L.M., Palik, B.J., Battaglia, M.A., D’Amato, A.W., Guldin, J.M., Swanston, C.W., Janowiak, M.K., Powers, M.P., Joyce, L.A., Millar, C.I., Peterson, D.L., Ganio, L.M., Kirschbaum, C., Roske, M.R., 2017. Adaptive Silviculture for Climate Change: A National Experiment in Manager-Scientist Partnerships to Apply an Adaptation Framework. J. For. 115, 167–178. https://doi.org/10.5849/jof.16-039

Naumann, S., Anzaldua, G., Berry, P., Burch, S., Davis, M., Frelih-Larsen, A., Gerdes, H., Sanders, M., 2011. Assessment of the potential of ecosystem-based approaches to climate change adaptation and mitigation in Europe. Final Rep. Eur. Comm. DG Environ.

Nicolas, L., 2013. Encodage et analyse de données qualitatives - Apports et limites du logiciel Sonal comme outil de recherche en SHS. Adjectif.net.

ONERC, 2015. L’arbre et la forêt à l’épreuve d’un climat qui change, La Documentation française. ed. Observatoire national sur les effets du réchauffement climatique, Paris, France.

Perez, P., Aubert, S., Daré, W., Ducrot, R., Jones, N., Queste, J., Trébuil, G., Van Paassen, A., 2010. Évaluation et suivi des effets de la démarche, in: La Modélisation d'accompagnement: Une Démarche Participative En Appui Au Développement Durable. Michel Étienne, pp. 153–181.

Porté, A., Bartelink, H.H., 2002. Modelling mixed forest growth: a review of models for forest management. Ecol. Model. 150, 141–188. https://doi.org/10.1016/S0304-3800(01)00476-8

Reckien, D., Eisenack, K., 2013. Climate Change Gaming on Board and Screen: A Review. Simul. Gaming 44, 253–271. https://doi.org/10.1177/1046878113480867

Redpath, S.M., Keane, A., Andrén, H., Baynham-Herd, Z., Bunnefeld, N., Duthie, A.B., Frank, J., Garcia, C.A., Månsson, J., Nilsson, L., Pollard, C.R.J., Rakotonarivo, O.S., Salk, C.F., Travers, H., 2018. Games as Tools to Address Conservation Conflicts. Trends Ecol. Evol. 33, 415–426. https://doi.org/10.1016/j.tree.2018.03.005

Röling, N., Maarleveld, M., 1999. Facing strategic narratives: In which we argue interactive effectiveness. Agric. Hum. Values 16, 295–308.

Scarlat, N., Dallemand, J., Taylor, N., Banja, M., Sanchez, J., Avraamides, M., 2019. Brief on biomass for energy in the European Union.

Spittlehouse, D.L., Stewart, R.B., 2004. Adaptation to climate change in forest management. J. Ecosyst. Manag. 4.

Tronquet, C., Grimault, J., Foucherot, C., 2017. Projet VOCAL - Potentiel et déterminants de la demande volontaire en crédits carbone en France. Etudes Clim. 32.

UNESCO, 2019. Chaîne des Puys - Limagne fault tectonic arena - UNESCO World Heritage Centre [WWW Document]. URL https://whc.unesco.org/en/list/1434 (accessed 10.5.19).

van Pelt, S.C., Haasnoot, M., Arts, B., Ludwig, F., Swart, R., Biesbroek, R., 2015. Communicating climate (change) uncertainties: Simulation games as boundary objects. Environ. Sci. Policy 45, 41–52. https://doi.org/10.1016/j.envsci.2014.09.004

Van Gameren, V., 2014. L'adaptation de la gestion forestière privée au changement climatique : le cas wallon. Sud-Ouest Eur. Rev. Géographique Pyrén. Sud-Ouest 63–75. https://doi.org/10.4000/soe.1093

Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P.D., Bommel, P., Prell, C., Zellner, M., Paolisso, M., Jordan, R., Sterling, E., Schmitt Olabisi, L., Giabbanelli, P.J., Sun, Z., Le Page, C., Elsawah, S., BenDor, T.K., Hubacek, K., Laursen, B.K., Jetter, A., Basco-Carrera, L., Singer, A., Young, L., Brunacini, J., Smajgl, A., 2018. Tools and methods in participatory modeling: Selecting the right tool for the job. Environ. Model. Softw. 109, 232–255. https://doi.org/10.1016/j.envsoft.2018.08.028

Weinstein, N.D., 1984. Why it won’t happen to me: perceptions of risk factors and susceptibility. Health Psychol. 3, 431.

Funding source: This work was supported by a grant from the French National Research Agency (ANR) as part of the “Investments d’Avenir” Program (LabEx BASC; ANR-11-LABX-0034). The funding source had no involvement in any of the research.

Declarations of interest: none.

Appendix A: ODD+D description of *Foster Forest* participatory simulations.

The extended "Overview, Design Concepts, and Details" (ODD+D) template was proposed as a standard protocol to describe and compare agent-based models that include human decision-making (Müller et al., 2013). Table C.1. is directly taken from the supplementary data of Müller et al. (2013).

Table A.1. ODD+D description of *Foster Forest* participatory simulations. Italic font denotes the text related to *Foster Forest* that was added to the original template.

Outline (→ template)		Guiding questions	Examples	Foster Forest *ODD+D Model description*
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?	Research question incl. test of hypothesis, system understanding, theory development, quantitative predictions, management or decision support, communication and learning (participatory modeling)	*In forestry, adaptation to climate change mostly focuses on timber production and technical changes.* Foster Forest *tracks complementary adaptations that can emerge from situations in which forest stakeholders are collectively confronted with the limitations of technical adaptations in a very pessimistic climate change scenario.*
		I.ii.b For whom is the model designed?	Scientists, students/teachers, decision makers, stakeholders	*Scientists, but it can also be used for educational or awareness-raising purposes by others.*
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	Agents / individuals (humans, institutions): types and subtypes, spatial units (grid cells), environment, collectives (groups of agents)	*Agents > five forest managers (one public forester from the French National Forests Office; one elected official of a municipality owning communal forests; two private landholders; one protected area manager. Spatial units > 5-ha forest plots, grouped in properties. Environment > trees are located on plots.*
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized?	<u>Of Agents:</u> identity number, age, sex, maximum age, memory, location, level of resources, ownership of land, (political) opinion, occupation, decision model (only mention the name of the strategy, which is explained later on), one agent represents one individual / one household / one farm / all individuals of one specific type, <u>of spatial units</u>: location, a list of agents in a cell, land owned by farmer, descriptor of environmental conditions (elevation,	*Cf. Fig. 2 in the main text.*

			vegetation cover, soil type), current land use of collectives: list of agents, specific actions Units of measurement	
		I.ii.c What are the exogenous factors / drivers of the model?	Disease, climate, lake water level, land cover change, tectonic disturbances, invasive species, legislation	*Climate change (see Appendix B), economic variations of the timber market (see Appendix C).*
		I.ii.d If applicable, how is space included in the model?	Not included, spatial implicit, spatial explicit, georeferenced (GIS)	*Spatial explicit, or "stylized"* sensu *(Le Page and Perrotton, 2017).*
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	One timestep represents one year and the simulations were run for 100 years, one grid cell represents 1 ha and the model landscape comprises 1000 x 1000 ha	*One timestep represents 10 years, and the simulations were run for three to four timesteps (30 to 40 years). One grid cell represents 5 ha, and the model landscape comprises 5 x 10 cells (250 ha).*
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	Self-explanatory names of the model's processes, including decision making processes, pseudo-code of the schedule, synchronous / asynchronous update	*Each timestep begins with players' decisions.* *1) Foresters can harvest and/or plant trees on each of their plots. They choose the hunting pressure to apply to their property.* *2) Once all five participants have managed their properties, the protected area manager indicates the newly registered plots under a conservation program.* *3) Land transactions can occur at the demand of participants.* *Each timestep follows with the computerized update of:* *4) the impacts of climate change.* *5) forest growth.* *6) soil fertility.* *7) carbon storage.* *8) the impacts of game grazing.* *9) agents' budgets.* *10) global parameters (standing volume, water quality, inhabitants' satisfaction level).*
II) Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?		*Companion modelling, adaptive management, ecosystem-based adaptation, social-ecological thinking. A forest growth model simulates the dynamics of 1-ha uneven-aged forest stands containing five different tree species of four diameters.*

		II.i.b On what assumptions is/are the agents' decision model(s) based?	Established theories (micro-economic models: homo oeconomicus, full / bounded rationality; cognitive models: social psychology, mental models; space-theory based models) real-world observations (mechanistic explanations / process-based understanding available; black-box, use of heuristics, statistical regression methods) ad-hoc rules (dummy rules, e.g. constancy assumption) combinations of theory and observations	*Agents' decisions are all taken by the human participants. Agents are bounded rational, use a form of inductive reasoning, and rely on heuristics (Crozier and Friedberg, 1977).*
		II.i.c Why is a/are certain decision model(s) chosen?	Data (non-) availability, pattern-oriented modeling, reference to other studies, theoretical considerations	*Lack of available data on how adaptations occur in the field.*
		II.i.d If the model / a submodel (e.g. the decision model) is based on empirical data, where does the data come from?	Participatory approaches (role playing games), household surveys, interviews, direct observations, statistical census, archives, GIS, field or lab experiments	*Data derive from previous field work (Fouqueray et al., 2020). Other data sources are described in Appendices A and B.*
		II.i.e At which level of aggregation were the data available?	Household / individual level, group level	*Individual level.*
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modeled? Are multiple levels of decision making included?	Name subjects (individuals agents / households, on communal level, top down decision maker) and objects of decisions, e.g.: Form of land use, distribution of labor, choices of buying and selling	*Forest stakeholders individually decide on tree removal and planting on each of their plots. They decide on the possible sale of a plot, and if they engage in a conservation program applicable to any eligible plots.*
		II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Rational choice (classical optimization approach, utility maximization), bounded rationality (satisficing approach), no objectives (routine based, trial and error)	*Agents pursue personal objectives fixed in the game and presented during the introductory brief (bounded rationality).*
		II.ii.c How do agents make their decisions?	Decision tree, utility function, random choice	*Agents compare their ecological (e.g., climatic prediction of the climatic scenario), social, and economic indicators step-by-step. They compare their current situation with past decisions as well as their neighbors' strategy.*
		II.ii.d Do the agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how?	Adaption of resource extraction level in dependence of ecological state of resource	*Yes. They use basic detailed budget information provided by the ABM, or a basic heuristic (which can be based on their personal experience) to decide if they continue with their current forestry operations.*

		II.ii.e Do social norms or cultural values play a role in the decision-making process?	Cultural norms, trust	*Yes. Social norms: public foresters are sit side by side, to reproduce the strong ties bounding them in real-life. Cultural norms: private foresters most often describe their forests as a legacy transmitted by their elders and to be transmitted to future generations.*
		II.ii.f Do spatial aspects play a role in the decision process?	Space-theory based models	*Yes. Private foresters tend to group their plots through land transactions.*
		II.ii.g Do temporal aspects play a role in the decision process?	Discounting, memory	*Yes. Agents have a memory of past climate catastrophes. They bear future impacts of climate change in mind when taking their management decisions.*
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Not at all / stochastic elements mimic uncertainties in agents' behavior / agents explicitly consider uncertain situations or risk	*Agents explicitly consider risks (e.g., they account for uncertainty of future climate conditions by favoring drought-resistant species). Stochastic elements mimic uncertainties of forest growth.*
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	Change of aspiration levels depending on past experiences	*No.*
		II.iii.b Is collective learning implemented in the model?	Evolution, genetic algorithms	*No.*
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?		*Exogenous variables: decadal projections of climate conditions and timber prices.*
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	(Multiple) resources (including working power, monetary resources, other income resources) and behavior of other agents	*Behavior of other agents is visible. Indicators of multiple resources are displayed at the end of each timestep (individual budgets, results of hunting decisions on grazing pressures, water quality, etc.)*
		II.iv.c What is the spatial scale of sensing?	Local, network, global (whole model space)	*Local (properties).*
		II.iv.d Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?	Sensing is often assumed to be local, but can happen through networks or can even be assumed to be global.	*All mechanisms are described in the participant's role booklet, and all participant receive the same introductive briefing.*

		II.iv.e Are costs for cognition and costs for gathering information included in the model?		*No.*
	II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Extrapolation from experience, from spatial observations	*Data on decadal climatic and economic conditions.*
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?		*No specific models other than the reasoning abilities of each individual as she/he would implement them in a comparable real-world situation.*
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	(External) uncertainty, (internal) capability of the agent	*External uncertainty.*
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Direct interactions, indirect interactions (mediated by the environment / the market, auction)	*Indirect interactions (e.g., movement of game, water quality, landscape esthetic value).*
		II.vi.b On what do the interactions depend?	Spatial distances (neighborhood), networks, type of agent	*Networks.*
		II.vi.c If the interactions involve communication, how are such communications represented?	Explicit messages (Matthews et al., 2007)	/
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	Centralized vs. decentralized, group based tasks	*No initial coordination network exists, but it can emerge from participants.*
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	Social groups, human networks and organizations	*No (a private/public foresters distinction has been discarded, since it does not affect individual decisions).*
		II.vii.b How are collectives represented?	Collective as emergent property vs. as a definition by the modeler (separate kind of entity with its own state variables and traits)	/
	II.viii Heterogen eity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	Would an exchange of one agent with another at the beginning have an effect on the simulation?	*Yes. Property size (number of plots), objectives, possibility to lease hunting rights, possibility to sell private plots (impossible for plots located in state, communal, or protected areas)*
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?		*No.*

	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?		*The evolution of soil quality and belowground carbon storage are partly randomized. Initial distribution of tree volumes is partly random.*
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected?		*During the whole simulation: behaviors and discussions are saved using audio recorders; a camera films the entire room; and the computer screen is video-captured.*
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)		*A pattern of monospecific or species-mixed forest plots emerge depending on the economic and climatic risk-aversion of the agents.*
III) Details	II.i Implementation Details	III.i.a How has the model been implemented?	Computer system, programming language / simulation platform, simulation runtime, development time	*In CORMAS, with SmallTalk language. See also the main text.*
		III.i.b Is the model accessible and if so where?	Homepage? (link)	*www.fosterforest.fr*
	III.ii Initialization	III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?	Types and numbers of entities including the agents themselves, values / random distribution of their state variables	*Five foresters with the same initial budget but unequal forest properties in terms of surface and trees distribution.*
		III.ii.b Is initialization always the same, or is it allowed to vary among simulations?		*Initialization is always the same.*
		III.ii.c Are the initial values chosen arbitrarily or based on data?	References to data if any, stakeholder choice	*Based on data. See the other Appendices.*
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?	Observed time series e.g. annual rainfall, time series generated by other models, not: parameter values, initial values of state variables	*Yes. See Appendices B and C.*
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	Equations, algorithms, additional information	*For the forest growth model, see Appendix B. For social, ecological, and economic processes, see Appendix C.*
		III.iv.b What are the model parameters, their dimensions and reference values?	Tables of parameters	*See Appendices B and C.*
		III.iv.c How were submodels designed or chosen, and how were they parameterized and then tested?	Justifications, references to literature, independent implementation, testing, calibration, analysis of submodels	*See Appendices B and C.*

References

Crozier, M., Friedberg, E., 1977. L'acteur et le système. Les Contraintes de l'action collective, Seuil. ed, Sociologie politique. Paris, France.

Fouqueray, T., Charpentier, A., Trommetter, M., Frascaria-Lacoste, N., 2020. The calm before the storm: How climate change drives forestry evolutions. For. Ecol. Manag. 460, 117880. https://doi.org/10.1016/j.foreco.2020.117880

Le Page, C., Perrotton, A., 2017. KILT: A Modelling Approach Based on Participatory Agent-Based Simulation of Stylized Socio-Ecosystems to Stimulate Social Learning with Local Stakeholders, in: Sukthankar, G., Rodriguez-Aguilar, J.A. (Eds.), Autonomous Agents and Multiagent Systems. Springer International Publishing, Cham, pp. 31–44. https://doi.org/10.1007/978-3-319-71679-4_3

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., Schwarz, N., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. Environ. Model. Softw. 48, 37–48. https://doi.org/10.1016/j.envsoft.2013.06.003

Appendix B: *Foster Forest*'s forest growth model

Model selection was based on three main criteria: (i) a model fast enough to run in less than 2 minutes between two rounds; (ii) a model incorporating the main ecological processes of forest growth (crowning, germination and mortality rates, etc.); (iii) a model reproducing participants' representations of climate change impacts, even if not fully realistic. We first considered various forest growth models (e.g., LANDIS, CAPSIS; Dufour-Kowalski et al., 2012; LANDIS-II Foundation, n.d.). Our phenomenologist approach placed greater emphasis on participants' perceptions of the impacts of climate change rather than on the best available knowledge and models of forest growth under climate change. Therefore, we opted for a simplified forest growth model tailored to our specific requirements.

1. A simplified forest growth model

Here, we consider a simple aggregated model of forest dynamics inspired by the articles of Kohyama and Takada (2009, 2012) and Mathias et al. (2015). Forest dynamics are modeled at a 1-ha scale, and tree competition for light is based on perfectly one-sided competition. The forest is made of four strata (x_1, x_2, x_3, x_4) composed of trees of the same diameters at breast height (DBH) (respectively, 7.5 cm, 25 cm, 45 cm, and 60 cm; hence x_1 is the lowest stratum and x_4 the highest). Contrarily to Mathias et al. (2015), in our model, trees can be harvested in any of the four strata.

The dynamics of species i is expressed in number of trees x_i in each stratum:

$$\begin{cases} \dfrac{dx_{4,i}}{dt} = h_{3,i}x_{3,i}\left(1 - u_i \displaystyle\sum_{i=a}^{e} g_{4,i}x_{4,i}\right) - x_{4,i}d \\ \dfrac{dx_{3,i}}{dt} = h_{2,i}x_{2,i}\left(1 - u_i \displaystyle\sum_{k=3}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) - h_{3,i}x_{3,i}\left(1 - u_i \displaystyle\sum_{i=a}^{e} g_{4,i}x_{4,i}\right) - x_{3,i}\left(d + z_i \displaystyle\sum_{i=a}^{e} g_{4,i}x_{3,i}\right) \\ \dfrac{dx_{2,i}}{dt} = h_{1,i}x_{1,i}\left(1 - u_i \displaystyle\sum_{k=2}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) - h_{2,i}x_{2,i}\left(1 - u_i \displaystyle\sum_{k=3}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) - x_{2,i}\left(d + z_i \displaystyle\sum_{k=3}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) \\ \dfrac{dx_{1,i}}{dt} = b_i(g_{3,i}x_{3,i} + g_{4,i}x_{4,i})\left(1 - s_i \displaystyle\sum_{k=2}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) - h_{1,i}x_{1,i}\left(1 - u_i \displaystyle\sum_{k=2}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) - x_{1,i}\left(d + z_i \displaystyle\sum_{k=2}^{4}\sum_{i=a}^{e} g_{k,i}x_{k,i}\right) \end{cases}$$

(Eq. B.1)

where

- i is one of the five species of interest (*a: Quercus robur, b: Quercus petraea, c: Fagus sylvatica, d: Pinus Sylvestris*, and *e:Pseudotsuga menziesii*);
- k is the mean DBH of each stratum;
- $g_{k,i}$ is the basal area of a tree of diameter k and species i;
- $h_{k,i}$ is the temporal rate at which a tree of stratum k switches to stratum $k+1$; it is reduced by asymmetric competition with higher strata expressed by parameter u (ha.m^{-2});
- d_i is the parameter related to species intrinsic mortality (t^{-1}); mortality is increased by asymmetric competition modeled by parameter z_i (t^{-1}.ha.m^{-2})
- b_i is the intrinsic recruitment rate (expressed in the number of individuals.m^{-2}.ha.t^{-1}); recruitment only occurs if there are trees of strata 3 and/or 4 on the stand; recruitment is sensitive to light interception by higher strata, as modeled by s_i (ha.m^{-2}).

2. Effects of participants' actions on forest growth and other indicators

The growth model described by Eq. B.1. does not account for all the ecological or technical processes included in the simulation. For instance, it does not take tree removal into account or the detrimental effects of grazing by wild animals on the recruitment rate in stratum 1. These effects were additionally fixed by the authors so as to obtain analogous results in terms of what is actually depicted in the field or described in gray literature.

Harvesting. During a round, the participants can harvest trees from the different categories of diameters and species of each plot. The number of trees was then retrieved from the plot. For instance, if the participant harvested 50 sessile oaks of diameter 3 on plot 42, the number of sessile oaks $x_{4,\,b}$ of that plot decreased by 50 before implementing a new run of the ABM.

Hunting. Hunting modifies the intensity of grazing by boars or deer. At every step, the participants select a high, medium or low hunting pressures to be applied on their plots. A high, medium, or low grazing rate induces the death of 30%, 10%, and 0% of trees of stratum 1, respectively. This outcome is calibrated by forestry reports and newspapers (FIBOIS Alsace, 2014; Odermatt, 2015; Saint-Andrieux, 1994) and from previous interviews conducted with foresters in the "Grand Est" and "Nouvelle-Aquitaine" regions (Fouqueray et al., 2020). Death processes are operated before performing a new run of the ABM.

Soil fertility. The growth model does not account for growth variation linked to the fertility of the soil (Eq. B.1.). Soil fertility is only accounted for during the initialization and update of the water quality indicator. In the ABM, the initial volume of trees located on medium fertility stands is the same for each category of diameter and species (e.g., every sessile oak of diameter 2 has the same volume). In low fertility stands, this initial volume was modified by a factor randomly chosen from 0.9 to 1, and in high fertility stands from 1 to 1.1.

3. Including the effects of climate change

After each step, the growth, recruitment, and death parameters were modified according to a very strong climate change scenario that was predetermined. The scenario did not relate to the existing forest scenarios for French regions but was created *ad hoc* for the needs of *Foster Forest*. In the climate scenario, the impacts of climate change are species-specific and especially account for the different sensitivities of tree species to drought. Species were ranked from the most sensitive species (beech, *Fagus sylvatica*) to the intermediate drought-aversive species (pedunculate oak, *Quercus robur*) and then the least sensitive species (sessile oak, *Quercus petraea*; pine, *Pinus sylvestris*; and Douglas fir, *Pseudotsuga menziesii*) (Direction des Ressources Forestières et al., 2017). The scenario is presented in Table B.1.

Table B.1. Temporal evolution of recruitment, growth, and death parameters per species.

	Quercus petraea			*Quercus robur*			*Fagus sylvatica*			*Pinus sylvestris*			*Pseudotsuga menziesii*		
	b	*h*	d	b	*h*	d	b	*h*	d	b	*h*	d	b	*h*	d
Round 2, compared to round 1 (2020-2030 > 2030-2040)	-3%	*-3%*	+3%	-3%	*-3%*	+3%	-3%	*-3%*	+3%	-3%	*-3%*	+3%	-3%	*-3%*	+3%
Round 3, compared to round 2 (2030-2040 > 2040-2050)	-7%	*-3%*	+5%	-9%	*-5%*	+7%	-17%	*-12%*	+12%	-12%	*-10%*	+10%	-7%	*-8%*	+10%
Round 4, compared to round 3 (2040-2050 > 2050-2060)	+5%	*0%*	-3%	+5%	*0%*	-3%	+5%	*+7%*	-3%	+5%	*'+5%*	0%	+5%	*+7%*	0%
Round 5, compared to round 4 (2050-2060 > 2060-2070)	0%	*+2%*	0%	0%	*+2%*	0%	0%	*+2%*	0%	0%	*+2%*	0%	0%	*+2%*	0%

Participants were informed about the limitations of the modeling approach in the introductory brief, which did not seem to be problematic for them (see section 5.2.3. in the main text). Participants could also consult scientific popularization articles provided by the facilitators to better understand the current knowledge on the issues at stake.

4. Model parameters

Eq. B.1. was solved as a system of difference equations using one-tenth of a year as the temporal step (i.e., $\Delta t = 0.1\ year$). As the virtual length of a round was 10 years in the participatory simulation, 100 iterations occurred between 2 rounds. The temporal parameters were first calibrated to fit to an annual reference and then brought back to one-tenth of a year. Similarly, the spatial parameters used in Eq. B.1. were first calibrated at a 1-ha scale and then revised to fit the 5-ha spatial scale used in the participatory simulation.

The initial parameters used in the growth model are displayed in Table B.2.

Table B.2. Parameters used in the forest growth model and the initialization of the *Foster Forest* agent-based model.

Class	Attribute	Value	Unit	Reference
Trees, regardless of species and age	b: intrinsic recruitment rate	Random float:] 0.05 ; 0.08 [	Number of individuals.m^{-2}.ha.t^{-1}	Redon et al., 2014
Trees, regardless of species and age	d: intrinsic mortality	8.0e-4	Number of individuals.t^{-1}	Csilléry et al., 2013
Trees of diameter 1	g: hectare basal area strata 1	0.004	m^2.ha^{-1}	(IFN, 2017) Data selection was restricted to the following administrative regions: Bretagne, Pays de la Loire, Normandie, Centre Val de Loire, Île de France, Hauts de France, Grand Est, Bourgogne-Franche-Comté.
Trees of diameter 2	g: hectare basal area strata 2	0.049		
Trees of diameter 3	g: hectare basal area strata 3	0.159		
Trees of diameter 4	g: hectare basal area strata 4	0.283		
Fagus1	h: rate of switchover from strata 1 to strata 2	0.00281	t^{-1}	
Pinus1		0.0022		
Pseudotsuga1		0.003		
QuercusP1		0.005		
QuercusR1		0.0044		
Fagus2	h: rate of switchover from strata 2 to strata 3	0.00458		
Pinus2		0.0028		
Pseudotsuga2		0.0042		
QuercusP2		0.01		
QuercusR2		0.0088		
Fagus3	h: rate of switchover from strata 3 to strata 4	0.00769		
Pinus3		0		
Pseudotsuga3		0.0071		
QuercusP3		0.013		
QuercusR3		0.0117		
Fagus1	Mean volume of a single tree	0.09	m^3	(IFN, 2017) Data selection was restricted to the following administrative regions: Bretagne, Pays de la Loire, Normandie, Centre Val de Loire, Île de France, Hauts de France, Grand Est, Bourgogne-Franche-Comté.
Fagus2		0.75		
Fagus3		2.96		
Fagus4		4.75		
Pinus1		0.1		
Pinus2		0.69		
Pinus3		1.5		
Pinus4		2.4		
Pseudotsuga1		0.09		
Pseudotsuga2		0.99		
Pseudotsuga3		3.17		

Pseudotsuga4		5.07		
QuercusP1		0.08		
QuercusP2		0.75		
QuercusP3		2.27		
QuercusP4		4		
QuercusR1		0.09		
QuercusR2		0.87		
QuercusR3		2.63		
QuercusR4		5.25		
Foster Forest ABM	Number of monospecific plots	25	/	
Fagus1	Number of trees of a given species and diameter on a forest plot	760 in pure stands, 58 in mixed stands	ha^{-1}	(IFN, 2017) Data selection was restricted to the following administrative regions: Bretagne, Pays de la Loire, Normandie, Centre Val de Loire, Île de France, Hauts de France, Grand Est, Bourgogne-Franche-Comté.
Fagus2		500 in pure stands, 21 in mixed stands		
Fagus3		110 in pure stands, 7 in mixed stands		
Fagus4		80 in pure stands, 4 in mixed stands		
Pinus1		1000 in pure stands, 43 in mixed stands		
Pinus2		600 in pure stands, 16 in mixed stands		
Pinus3		300 in pure stands, 3 in mixed stands		
Pinus4		/		
Pseudotsuga1		200 in pure stands		
Pseudotsuga2		190 in pure stands		
Pseudotsuga3		170 in pure stands		
Pseudotsuga4		/		
QuercusP1		84 in mixed stands		
QuercusP2		400 in pure stands, 27 in mixed stands		
QuercusP3		250 in pure stands, 9 in mixed stands		
QuercusP4		300 in pure stands, 2 in mixed stands		

QuercusR1		600 in pure stands, 47 in mixed stands		
QuercusR2		400 in pure stands, 25 in mixed stands		
QuercusR3		250 in pure stands, 7 in mixed stands		
QuercusR4		300 in pure stands, 2 in mixed stands		
Fagus	s: recruitment sensitivity to light interception	0.0167	$ha.m^{-2}$	Thomas Cordonnier (personal communication) and Mathias et al. (2015)
Pinus		0.0222		
Pseudotsuga		0.0182		
QuercusP		0.0182		
QuercusR		0.02		
Fagus	u: growth reduction by asymmetric competition from higher strata	0.02	$ha.m^{-2}$	Thomas Cordonnier (personal communication) and Kunstler et al. (2011)
Pinus		0.0286		
Pseudotsuga		0.0222		
QuercusP		0.0222		
QuercusR		0.025		
Fagus	z: death increase due to asymmetric competition from higher strata	1.0e-4	$ha.t^{-1}.m^{-2}$	Mathias et al., 2015
Pinus		0.00143		
Pseudotsuga		0.00111		
QuercusP		0.00111		
QuercusR		0.00125		

References

Direction des Ressources Forestières, Gembloux Agro-Bio Tech, Gestion des Ressources forestières (Université de Liège), Earth and Life Institute, Environmental Sciences (Université Catholique de Louvain), Forêt Wallonne, 2017. Fichier écologique des essences [WWW Document]. URL https://fichierecologique.be/#!/ (accessed 9.29.19).

Dufour-Kowalski, S., Courbaud, B., Dreyfus, P., Meredieu, C., de Coligny, F., 2012. Capsis: an open software framework and community for forest growth modelling. Ann. For. Sci. 69, 221–233. https://doi.org/10.1007/s13595-011-0140-9

FIBOIS Alsace, 2014. Le déséquilibre forêt-gibier Son coût pour la forêt en Alsace.

Fouqueray, T., Charpentier, A., Trommetter, M., Frascaria-Lacoste, N., 2020. The calm before the storm: How climate change drives forestry evolutions. For. Ecol. Manag. 460, 117880. https://doi.org/10.1016/j.foreco.2020.117880

Kohyama, T., Takada, T., 2009. The stratification theory for plant coexistence promoted by one-sided competition. J. Ecol. 97, 463–471. https://doi.org/10.1111/j.1365-2745.2009.01490.x

Kohyama, T.S., Takada, T., 2012. One-sided competition for light promotes coexistence of forest trees that share the same adult height. J. Ecol. 100, 1501–1511. https://doi.org/10.1111/j.1365-2745.2012.02029.x

LANDIS-II Foundation, n.d. LANDIS-II Forest landscape model [WWW Document]. URL https://www.landis-ii.org/home (accessed 12.15.21).

Mathias, J.-D., Bonté, B., Cordonnier, T., de Morogues, F., 2015. Using the Viability Theory to Assess the Flexibility of Forest Managers Under Ecological Intensification. Environ. Manage. 56, 1170–1183. https://doi.org/10.1007/s00267-015-0555-4

Odermatt, O., 2015. Les périodes critiques pour l’abroutissement. La Forêt 68, 10–13.

Saint-Andrieux, C., 1994. Dégâts forestiers et grand gibier. 1. Reconnaissance et conséquences. Supplément Bull. Mens. Off. Natl. Chasse.

Appendix C: Consequences of participants' decisions on ecological, social and economic processes

1. Soil fertility

Soil fertility is considered at the stand level. It increases in the absence of silvicultural operations during one step; it decreases in the case of clearcutting, slash removal, or monospecific planting of Scots pines or Douglas fir; otherwise, it remains constant (Fig. C.1.).

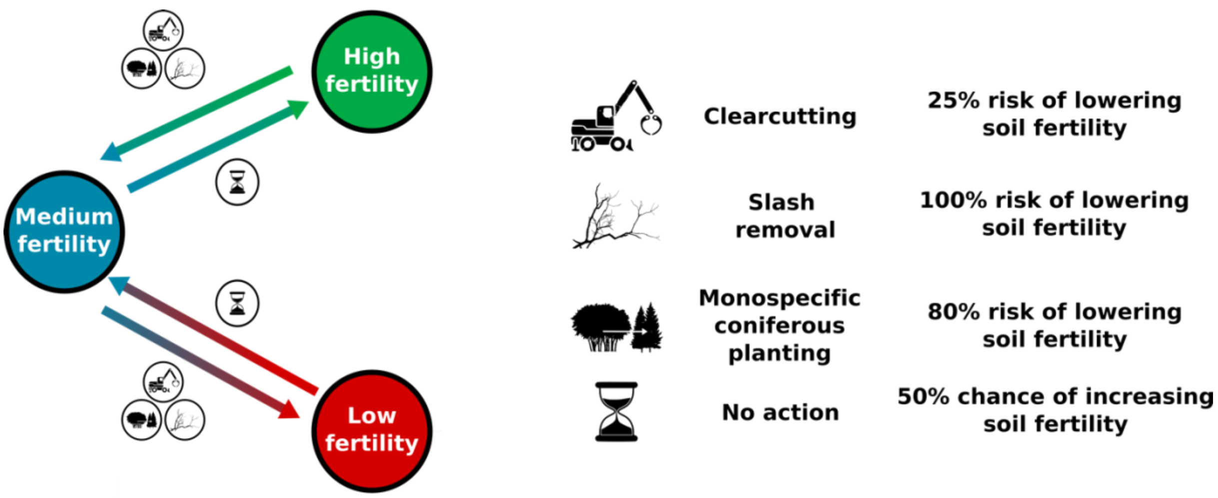


Fig. C.1. Evolution of a plot's soil fertility.

2. Water quality

Water quality is calculated at the end of a round before launching the calculations of tree growth (see Appendix B). The initial water quality is taken as a reference. Water quality is then arbitrarily calculated as follows (weighting results from discussions with foresters and mayors in charge of water syndicates):

$$w_j = \frac{2m_j - 2c_j - q_j}{w_0} \qquad \text{(Eq. C.1.)}$$

where:

- w_j is the water quality at the beginning of round j;
- m_j is the proportion of mature trees in the whole forest at the beginning of round j:
  $m_j = \frac{x_3 + x_4}{x_1 + x_2 + x_3 + x_4}$ where x_k is the number of trees of diameter k in the whole forest;
- c_j is the proportion of coniferous trees in the whole forest at the beginning of round j:

$c_j = \frac{x_{3,d}+x_{4,d}+x_{3,e}+x_{4,e}}{x_2+x_3+x_4}$ where $x_{k,i}$ is the number of trees of diameter k and species i in the whole forest (*d: Pinus sylvestris* and *e:Pseudotsuga menziesii*), and x_k is the number of trees of diameter k in the whole forest;

- q_j is the proportion of the 50 plots with low soil fertility.

3. Carbon storage and flows

Carbon flows were calculated as the difference in carbon stocks between two consecutive time steps at the plot level. Total carbon storage on a plot was the sum of aboveground and belowground carbon stocks. Aboveground carbon was approximated as the standing volume of trees for all four strata (discarding deadwood) and evolved according to the growth model detailed in Appendix B. The initialization of belowground carbon stocks was inspired by Jonard et al. (2017) and Lal (2005). It randomly diminished from 5 to 10% in the case of slash removal, clearcutting, or planting in order to reflect soil disturbances provoked by logging machines and soil preparation.

4. Inhabitants' satisfaction level

Inhabitants' level of satisfaction was incorporated as a proxy of the esthetic value of the forest landscape. It draws on discussions with public and private foresters of the natural regional park of the "Vosges du Nord" in September 2018. In the ABM, the satisfaction indicator v is calculated at the whole forest level:

$$v = \frac{1-(p_{pure}+p_{Douglas\,fir})}{p_{tot}} \qquad \text{(Eq. C.2.)}$$

where:

- p_{pure} is the number of monospecific plots;
- $p_{Douglas}$ is the number of monospecific Douglas fir plots; Douglas fir, an exogenous species in France, is often despised by local populations (Ferron, 2014) and was consequently counted twice in v;
- p_{tot} is the total number of plots (p_{tot} = 50).

5. Initialization of social and ecological parameters

The initial parameters used in the growth model to set up the parameters of the other classes of the ABM are displayed in Table C.1.

Table C.1. Ecological and social parameters used in *Foster Forest*.

Class	Attribute	Value	Unit	Reference
Forester managers	Budget	0	/	Fixed by authors
Foster Forest ABM	Number of plots	50	/	Fixed by authors
Foster Forest ABM	Inhabitants' satisfaction level	0.5	/	Fixed by authors
Foster Forest ABM	Initial number of plots with a conservation program of old-growth trees	0	/	Fixed by authors
Plot	Aboveground carbon storage	Sum of tree volumes	$MgC.ha^{-1}$	Jonard et al., 2017
Plot	Belowground carbon storage	91.2 if pure *Pseudotsuga* stand, 96.0 in the presence of *Pinus*, otherwise 72.6	$MgC.ha^{-1}$	Jonard et al., 2017
Plot	Certificate of sustainable management	0	Initial number of plots with ongoing certification	Fixed by authors
Plot	Soil fertility	9 in low fertility, 36 in medium fertility, 5 in high fertility	/	Fixed by authors
Property	Grazing rate	High (private owner 1), medium (private owner 2, mayor, protected area manager), low (public forester of the National Forest Office)	/	Fixed by authors

6. Economic parameters

6.1. Timber and carbon prices

The evolution of prices depends on an economic and political narrative announced before the beginning of each round. For instance, in 2020, the value of deciduous species decreases because of droughts in the previous decade, that entailed higher stocks of beech and oaks. The rising demand for fuelwood was accounted for in the evolution of prices, following prospective works from Hamrick and Gallant (2018), Lewis (2018), and World Bank et al. (2017), that also served for setting the prices of carbon storage. We draw on CNPF (2019) and on many discussions with forest professionals to set plausible prices of silvicultural operations.

Species	Diameter	Initial prices 2020-2029	Round 2 2030-2040	Round 3 2040-2050	Round 4 2050-2060	Round 5 2060-2070
Sessile oak (€/m^3)	1	14	-20%	+50%	-10%	-7%
	2	14				
	3	62				
	4	223				
Pedonculate oak (€/m^3)	1	14	-20%	+50%	-10%	-7%
	2	14				
	3	62				
	4	223				
Beech (€/m^3)	1	15	0%	-20%	+50%	-60%
	2	21				
	3	41				
	4	41				
Pine (€/m^3)	1	11	0%	0%	+20%	-10%
	2	28				
	3	28				
	4	28				
Douglas fir (€/m^3)	1	30	0%	0%	+20%	-10%
	2	30				
	3	40				
	4	40				
Carbon storage (€/CO_{2eq})		18	+178%	+14%	+9%	+34%
Silvicultural operations		Depends on the silvicultural treatment. Detailed in players' leaflet.	0%	+20%	0%	0%

Table C.2. Foster Forest's economic parameters – timber and carbon sales. The percentages of evolution refer to the previous round, not to the initialization of the game. Timber prices relate to standing, rough trees.

6.2. Land sales

Land sales occur at the end of a round. Participants state their potential interest in selling or buying forest plots. If an agreement is reached between two players, then the landownership changes and the financial transfers occurs. Participants can rely on the land prices shown in Table C.4., inspired from Société Forestière and Terres d'Europe-Scafr (2018).

	Plot(s) number	**Value (€/plot)**
Land price *(private plots only, public plots are not transferable)*	2 or less	19,450
	2 to 5	18,150
	6 to 10	22,500
	More than 10	40,150
	Amount of the financial transfer	**Additional cost (% of the value)**
Additional state taxes and notary costs	0 to 6,500 €	3.95%
	6 500 to 17,000 €	1.63%
	17,000 to 60,000 €	1.09%
	More than 60,000 €	0.81%

Table C.3. ***Foster Forest's*** **economic parameters – land sales.**

References

CNPF, 2019. CNPF - Centre national de la propriété forestière [WWW Document]. URL https://www.cnpf.fr/ (accessed 6.24.19).

Ferron, J.-L., 2014. Le Douglas, nouvelle ressource nationale. Rev. For. Fr. Fr.], ISSN 0035. https://doi.org/10.4267/2042/56059

Hamrick, K., Gallant, M., 2018. Voluntary Carbon Markets Insights: 2018 Outlook and First-Quarter Trends. Ecosystem Marketplace, Forest Trends, Washington, DC, USA.

Jonard, M., Nicolas, M., Coomes, D.A., Caignet, I., Saenger, A., Ponette, Q., 2017. Forest soils in France are sequestering substantial amounts of carbon. Sci. Total Environ. 574, 616–628. https://doi.org/10.1016/j.scitotenv.2016.09.028

Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manag. 220, 242–258. https://doi.org/10.1016/j.foreco.2005.08.015

Lewis, M.C., 2018. Carbon countdown - Prices and Politics in the EU-ETS. Carbon Tracker Initiat. 74.

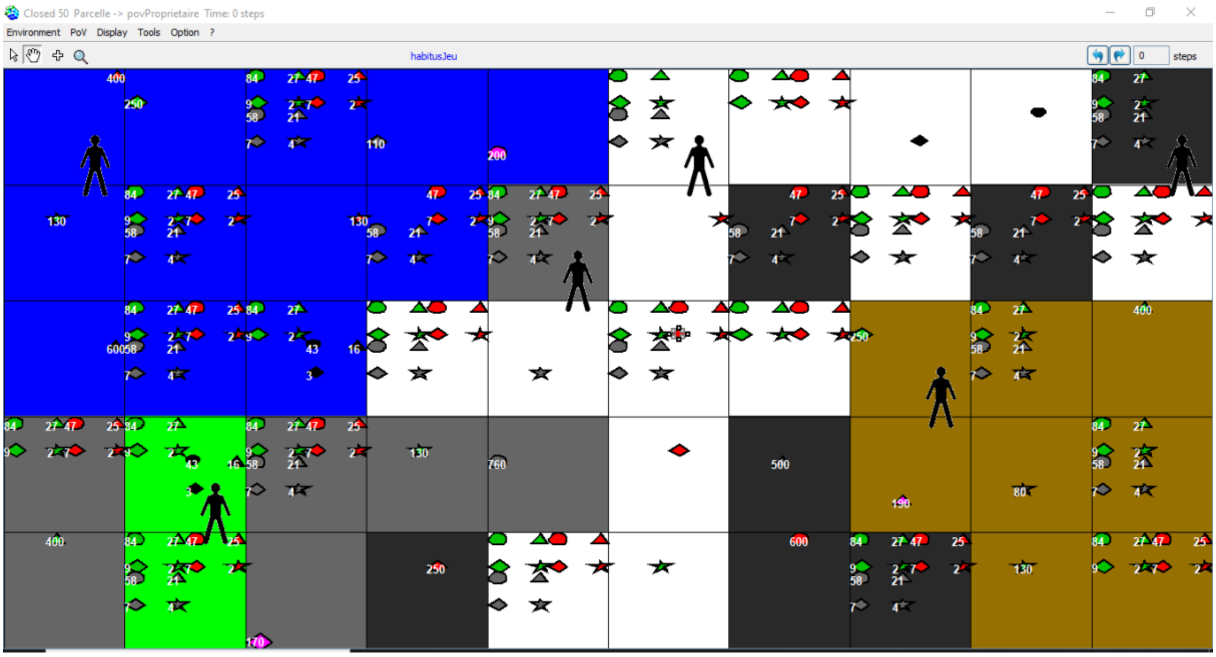
Société Forestière, Terres d'Europe-Scafr, 2018. Le marché des forêts en France - Indicateur 2018.

World Bank, Ecofys, Vivid Economics, 2017. State and Trends of Carbon Pricing 2017. World Bank Group - Climate change, Washington DC.

Appendix D: Visual interfaces used in *Foster Forest*

1. Interface displaying plots' features (used anytime)

The projection of the forest map on a wall can display different features, such as plot ownership, soil quality, eligibility to a conservation program, *etc*. Plot colors vary depending on the variable considered (Fig. D.1.).



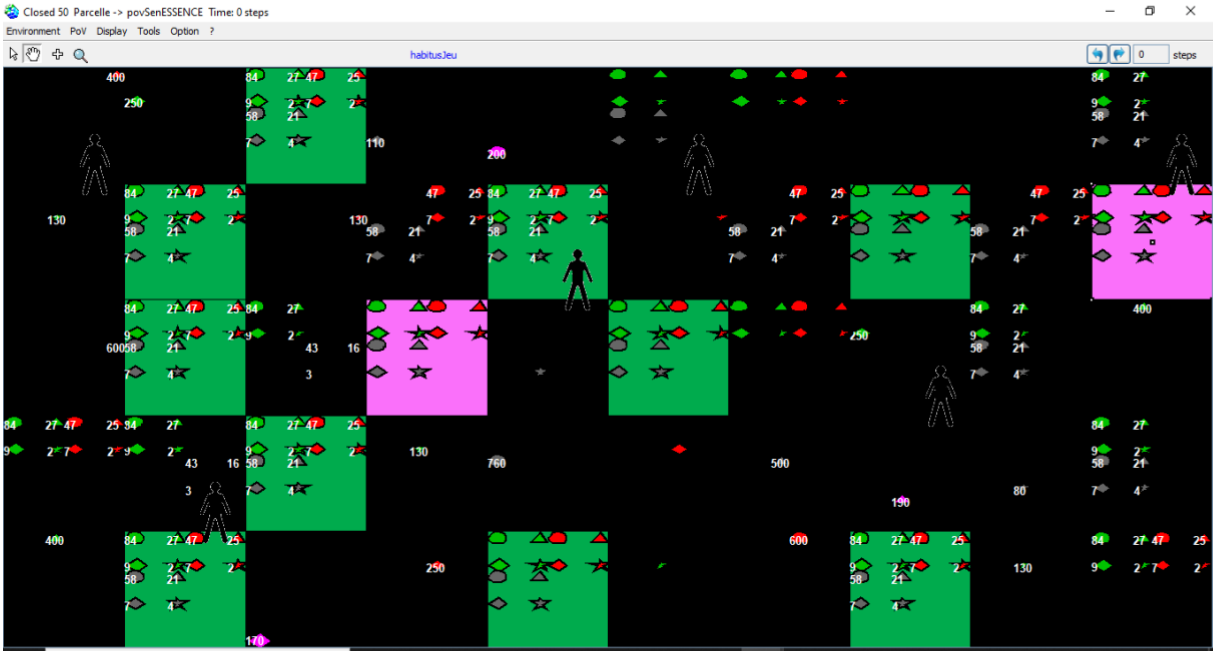


Fig. D.1. *Foster Forest* main interface. The interface displays different information at the demand of the players. Top map: plot ownership. Bottom map: in green, plots eligible to the conservation program; in pink, plots already included in the conservation program. Symbols (circles, triangles, diamonds and stars), colors (green, red, gray, black and pink) and figures respectively refer to the diameters, species and number of the trees located on the plots. Black silhouettes represent the five players. (A sixth avatar, standing on a white plot, reminds the participants of the existence of very small, unmanaged, private forests.)

2. Interface for the implementation of players' decisions (during a round)

Players have a set of possible actions that either regard silvicultural operations (plant trees, remove trees, *etc.*) or not (hunt, trade plots, engage in a certification program of sustainable forest management, *etc.*). They can also do nothing. Except for hunting, all decisions are taken at the plot level.

Fig. D.2. presents the interface for silvicultural actions. It reminds the player of the tree inventory, by species and diameters, and allows general or specific actions to be taken. Other interfaces are used for non-silvicultural actions.

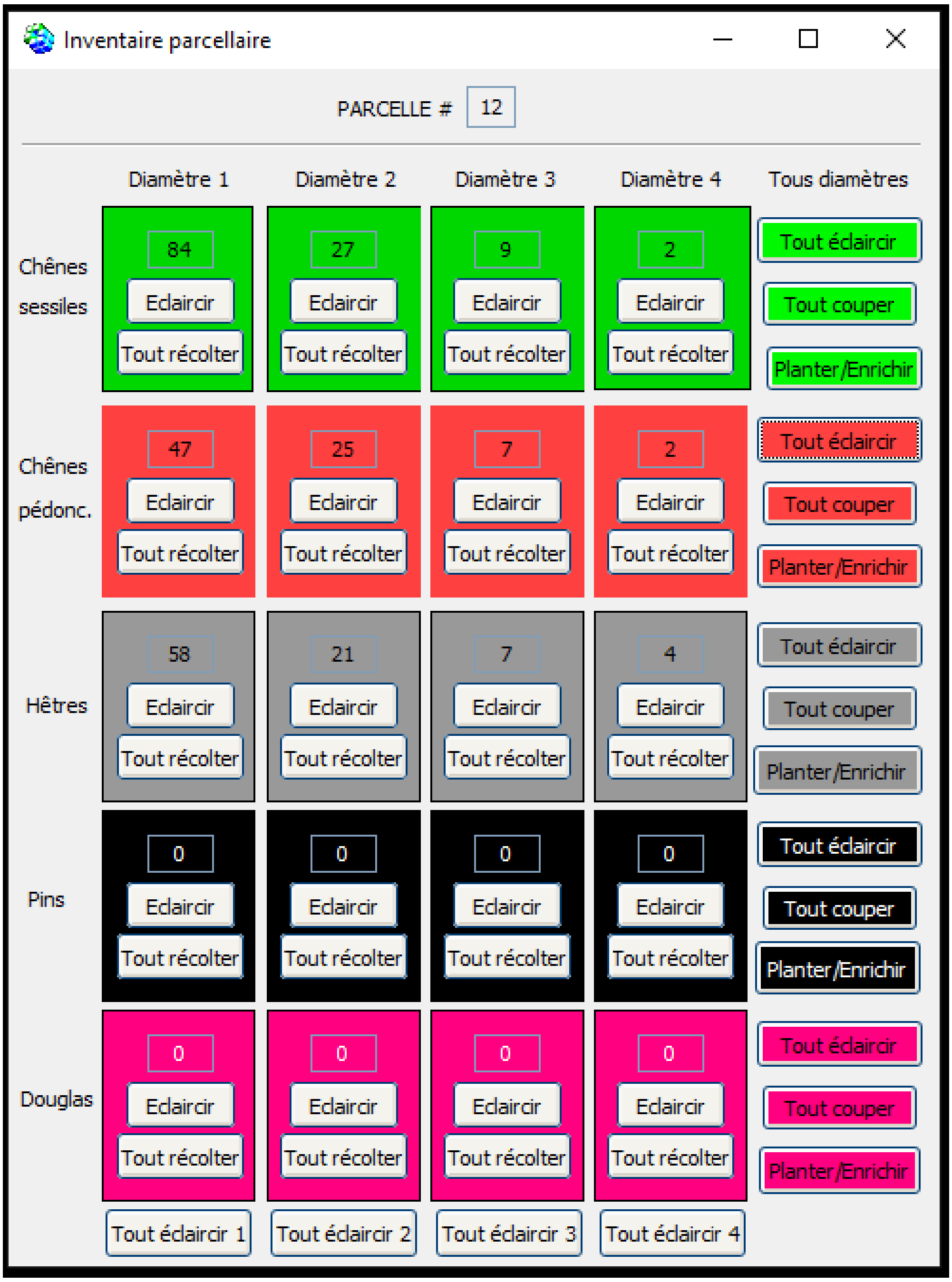


Fig. D.2. ***Foster Forest*** **decision interface for silvicultural operations on the twelfth plot.** This interface opens with a simple click on a plot.

3. Interface for the evolution of social, ecological and economic indicators (between two rounds)

General and individual indicators evolve depending on the actions undertaken at the previous round (Fig.D.3). Feedback loops act on the evolution of many indicators. For instance, if a high level of hunting pressure was applied to a property, but not to the neighboring properties, its overgrazing damages due to hunt game will still be high.

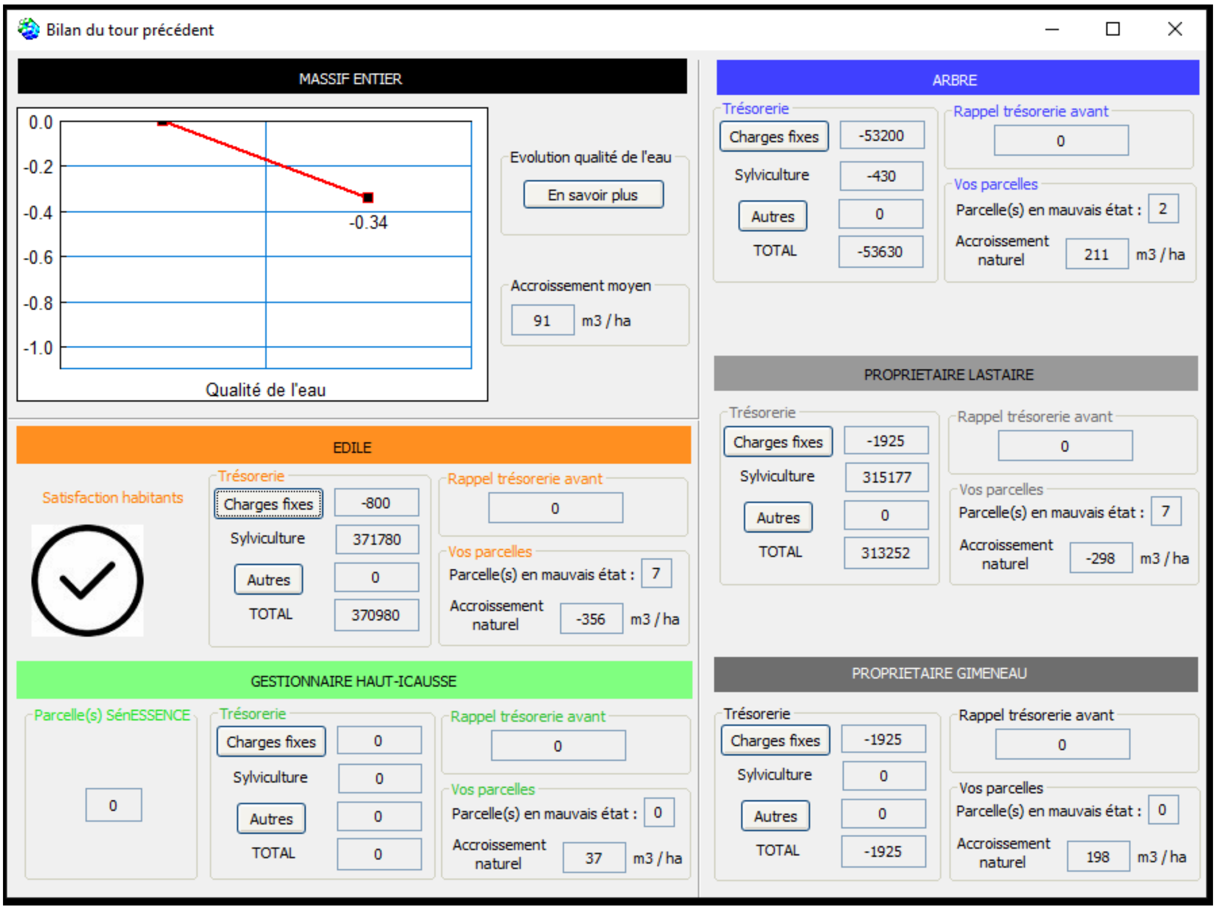


Fig. D.3. *Foster Forest* indicators interface. General information is displayed under the black label, whereas colored labels are player-specific. For instance, the “tick” logo under the orange label symbolizes the satisfaction level of the population, regarding the esthetic state of the forest landscape. Clicking boxes allows for detailed explanation on the evolution of various indicators.