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

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4
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16
17 **Abstract:**

18
19 The adaptive capacity of forests and foresters to overcome the adverse effects of climate change
20 remains highly uncertain despite intense research efforts. While foresters are often invited “not
21 to put all their eggs in one basket,” adaptation strategies to climate change mostly depend on
22 silvicultural diversification. To explore how socioeconomic adaptive tools can complement
23 these technical evolutions in forestry, we designed an interdisciplinary and participatory
24 simulation of forest management combining a role-playing game, ecological models of forest
25 evolution, and a severe climate change scenario. Participants from French natural parks and
26 forest organizations responded positively to its multiple applications. Here, we investigate the
27 technical and timber-focused framing of climate change by forest managers. We also analyze
28 participants’ negotiations when attempting to change the simulation rules of forest
29 management. Drawing on this experience, we highlight how establishing a payment system for
30 ecosystem services can reduce financial imbalance driven by climate change.

33 **Highlights:**

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

40

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

43

44 **Software availability:**

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

52 1. Introduction

53
54 The reality of climate change is now certain, although the magnitude of its spatial and
55 temporal impacts on the environment is not (IPCC, 2021). As one of the most important
56 ecosystems on the planet, forests will face profound long-term changes such as modified species
57 assemblages to an extent that is still unpredictable (García-Valdés et al., 2020; Lindner et al.,
58 2010). In the short to medium term, the productivity of forests in southern and eastern Europe
59 is expected to worsen because of the decreased health of forests caused by rarer cold extremes
60 and more frequent heat waves (Bréda et al., 2006; Ciais et al., 2005; Lindner et al., 2010). The
61 interaction of these hazards and phenological changes with introduced and native pathogens is
62 another matter of concern, with a great potential for damage (Bakys et al., 2009; Futai, 2013).
63 Hence, it is unclear whether forest species will have sufficient adaptive capacity to cope with
64 climate change (Aitken et al., 2008; Corlett and Westcott, 2013). For instance, the ability of
65 tree populations and species to overcome climate change is still being discussed (Alberto et al.,
66 2013). As a result, forest managers are trying to develop complementary adaptation strategies
67 (Keenan, 2015; Millar et al., 2007) to maintain the numerous ecosystem services (ES) provided
68 by forests such as timber production, leisure activities, carbon storage, and water filtering
69 (Brockerhoff et al., 2017). A key feature of robust anthropogenic adaptation is accounting for
70 the uncertainties of climate change: in a highly uncertain context, foresters can favor risk
71 dilution by using different tree species, ages, and silvicultural systems (Kennedy and Koch,
72 2004; Naumann et al., 2011). Instead of optimizing the performance of a forest stand, this “bet-
73 hedging” approach seeks to minimize ES loss (Spittlehouse and Stewart, 2004).

74 The issue of climate change is taken seriously in the field of forest sciences, and multifarious
75 research projects aim to develop a series of readily available adaptation options (Bolte et al.,
76 2009; Fouqueray and Frascaria-Lacoste, 2020; Keenan, 2015; Millar et al., 2007) or refine
77 predictive models of forest growth under climate change (Härkönen et al., 2019). To assess the
78 operability of these innovations, researchers can rely on an active network of forest landholders
79 and managers eager to participate in experimental tests, as demonstrated by many studies
80 conducted in France (CNPF, 2016), Europe (Kolström et al., 2011), and the United States
81 (Nagel et al., 2017). However, there is a difference between studies that expand existing
82 knowledge on the potential range of adaptation strategies and those that explore what is
83 currently being undertaken in the field. The available literature on what foresters are actually
84 doing to prepare for climate change is scarce. Based on individual interviews and
85 questionnaires, it shows that field practitioners do not wait for research outcomes to change

86 their management practices (Fouqueray et al., 2020; Kolström et al., 2011; Van Gameren,
87 2014). It also stresses the emphasis placed on timber production and forestry technical changes
88 such as species replacement or the tree density of forest stands, which is a typical trend in
89 forestry (Dobbertin and Nobis, 2010).

90 Two conclusions arise from this state of the art. First, the interactions between the different
91 forest stakeholders in the adaptation process have been scarcely examined to date. When
92 adapting, forest managers gear their silvicultural practices toward the provision of one or
93 multiple target ES (Duncker et al., 2012), which can positively or negatively affect the
94 management success of the neighboring stands: for instance, a preference for hunting in one
95 place can threaten the regeneration of trees in another. A forester can also be inspired by
96 management changes made by another forester, or they can develop ideas together that would
97 not have emerged otherwise. Second, several articles stress the value of thinking outside the
98 box and considering non-technical changes as complementary mechanisms (Hallegatte, 2009;
99 Jacobs et al., 2015; Naumann et al., 2011). For instance, as foresters draw most of their financial
100 resources from timber production, they will be at risk of climate change threatening the
101 productivity of trees. To balance their sources of revenue, foresters can look toward insights
102 from other disciplines as opposed to the forest sciences alone. For instance, they can look
103 toward the social and economic sciences to adopt economic tools for timber sales by adding
104 value to timber products through quality labels or turning toward insurance and supply contracts
105 with climate-related clauses, among others. Foresters can also diversify their income by
106 investing in ES other than timber production such as carbon storage contracts (Tronquet et al.,
107 2017).

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

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

143 In the following sections, we introduce the conceptual framework used to decide modeling
144 choices. We then present the ABM and RPG behind *Foster Forest*'s participatory simulations.
145 We conclude with the description and discussion of the results relating to the nine French study
146 cases. France was chosen as our study area, because its forestry situation is particularly relevant
147 to climate change adaptation: the country has the fourth largest area of forests in Europe
148 (165,000 km²) (MAAF, 2017). Its legal regulations and public policies are also representative
149 of countries adopting a multifunctional management of forests with the simultaneous provision
150 of timber production, leisure activities, and biodiversity conservation (Légifrance, 2012). The
151 timber industry and forest management provide numerous jobs, whether in private stands (75%
152 of the surface) or in public forests (MAAF, 2017). Thus, adaptation is of great importance and

153 is acknowledged in numerous public policies (MAAF, 2017; ONERC, 2015) and research
154 projects (Fouqueray and Frascaria-Lacoste, 2020).

155

156 **2. Collective construction of the conceptual model**

157

158 *2.1. A social-ecological framing of stakeholders' interdependencies*

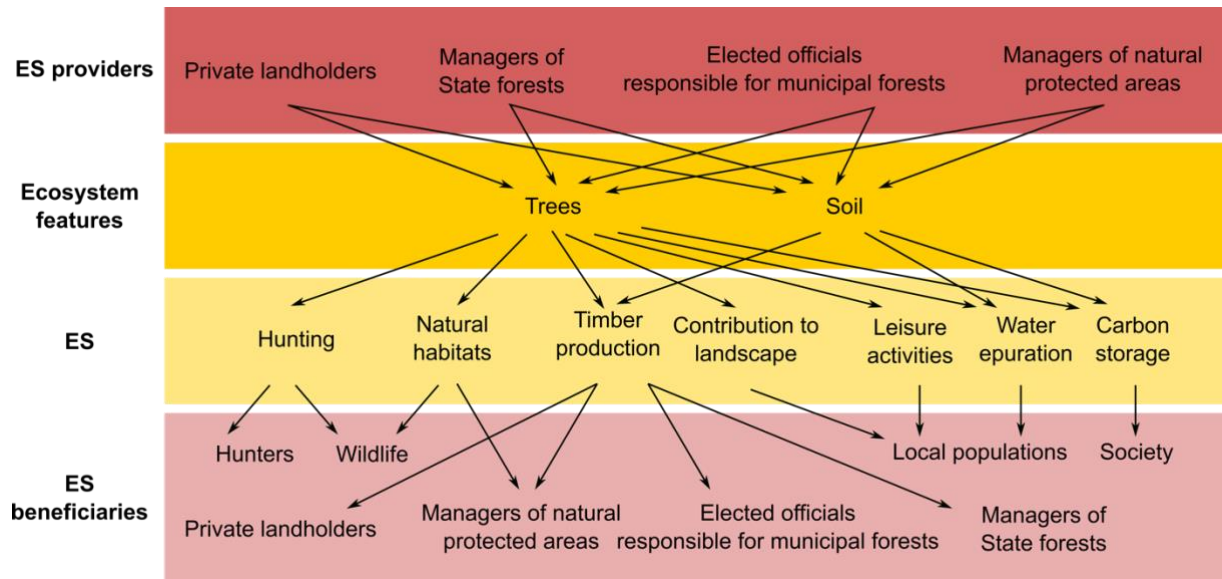
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160 The analytical conceptual framework developed by Barnaud et al. (2018) for studying ES,
161 social interdependencies, and collective action in SES inspired the design of *Foster Forest*. ES
162 are at the core of this framework, which stresses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

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

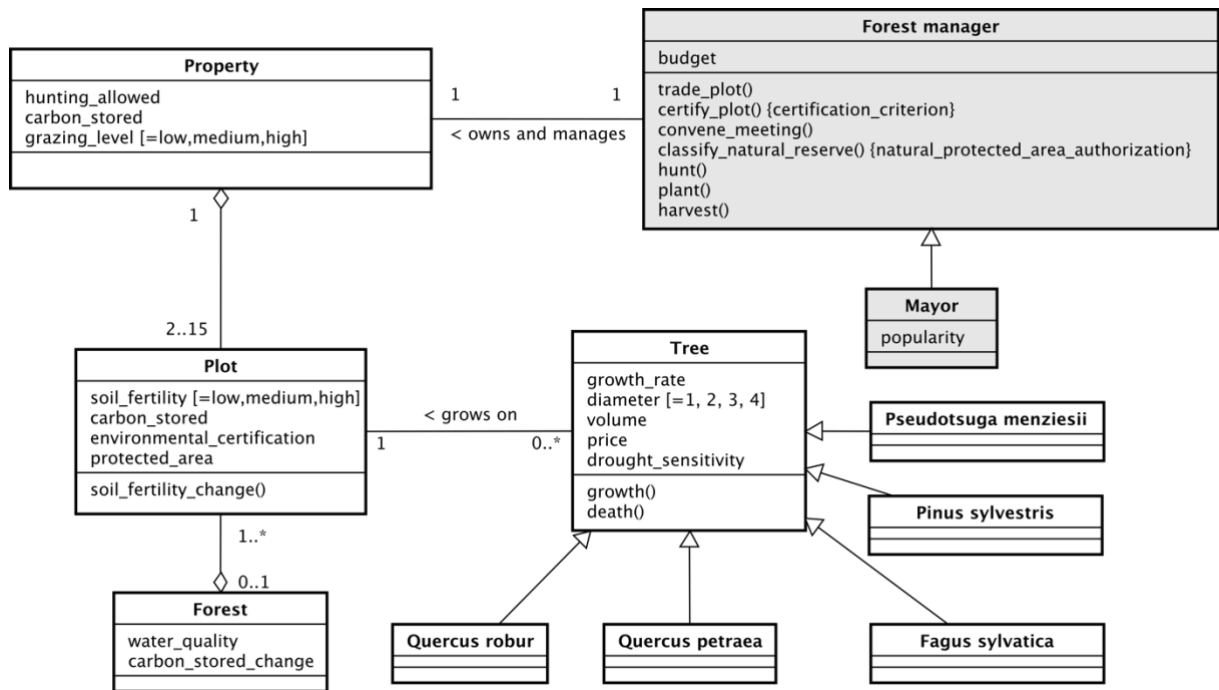
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Figure 1. A simplified version of the *Foster Forest* conceptual model. ES: ecosystem services. Forest ES that do not relate to adaptation issues such as erosion control were not included in the model.



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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

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

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

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

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

222

223 *2.3. A model restricted to five providers of ecosystem services*

224

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

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

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

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

252

253 **3. Agent-based model behind *Foster Forest***

254

255 *Foster Forest* is a hybrid composite simulation (Le Page et al., 2011), which combines
256 features of both ABM and RPG. It is both hybrid and composite because of its combination of
257 autonomous avatars of agents, humans controlling non-autonomous avatars (or their

258 computerized representations), and semi-autonomous agents (humans with limited options of
259 control). Here, we present the ABM on which *Foster Forest* relies.

260

261 3.1. Model classes and calibration sources

262

263 *Foster Forest*'s ABM includes spatial entities (plots and properties), semi-autonomous
264 social entities (foresters), and physical entities (trees) (Fig. 2). The simulation environment is
265 stylized, which means that the characteristics of each of the classes are proportional to French
266 temperate forests (Le Page and Perrotton, 2017). For instance, the initial distribution of pure or
267 species-mixed forest stands is based on empirical data from the National Forest Inventory (IFN,
268 2017). Abstract and representative environments were discarded for two reasons. First, we
269 needed a prospective tool to allow for comparisons between different regions in the same
270 legislative and economic context, namely France. Abstract or representative environments
271 could not lead to comparisons of regional social-ecological frameworks (Barreteau et al., 2001).
272 Second, a stylized environment distances participants from the issues that they face on a daily
273 basis and facilitates their reflective behaviors during the participatory simulation (Étienne,
274 2010).

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

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

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

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

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

300

301 3.2. Computerized processes and players' actions

302

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

309

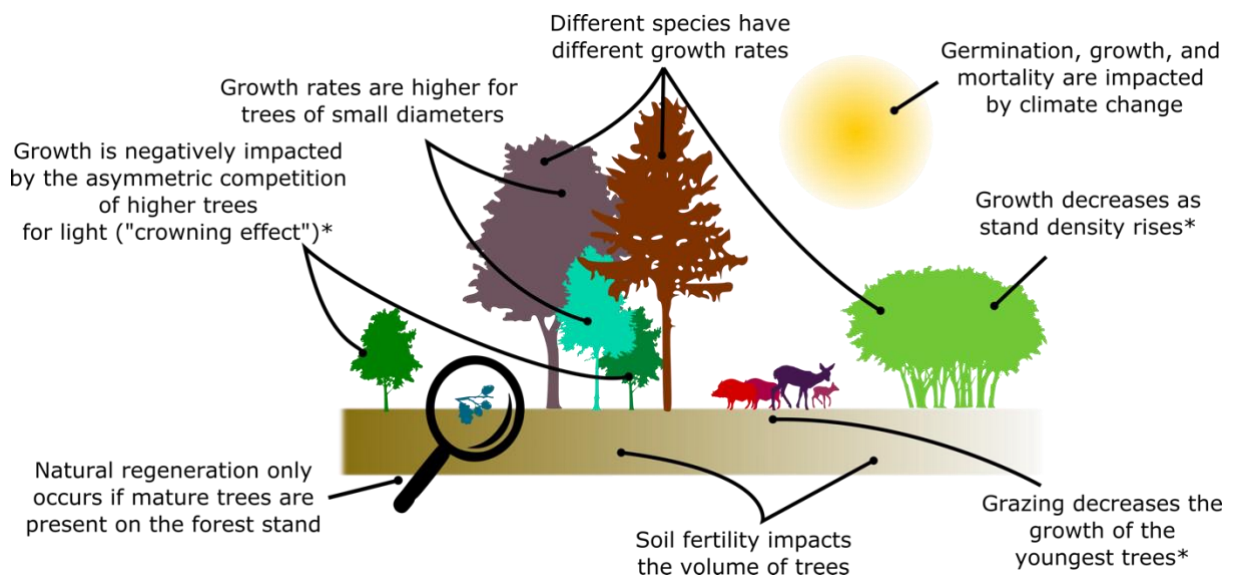
310 3.2.1. Simulation of forest growth

311

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

319

320



321

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

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

325

326 The forest growth model used in *Foster Forest*'s ABM is inspired by Kohyama and Takada
 327 (2012) as well as Mathias et al. (2015). The growth model, presented in Appendix B, simulates
 328 the dynamics of 1 ha of uneven-aged forest stands containing five different tree species of four
 329 diameters. Its execution by CORMAS was very rapid, which avoided interruptions during the
 330 participatory simulations.

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

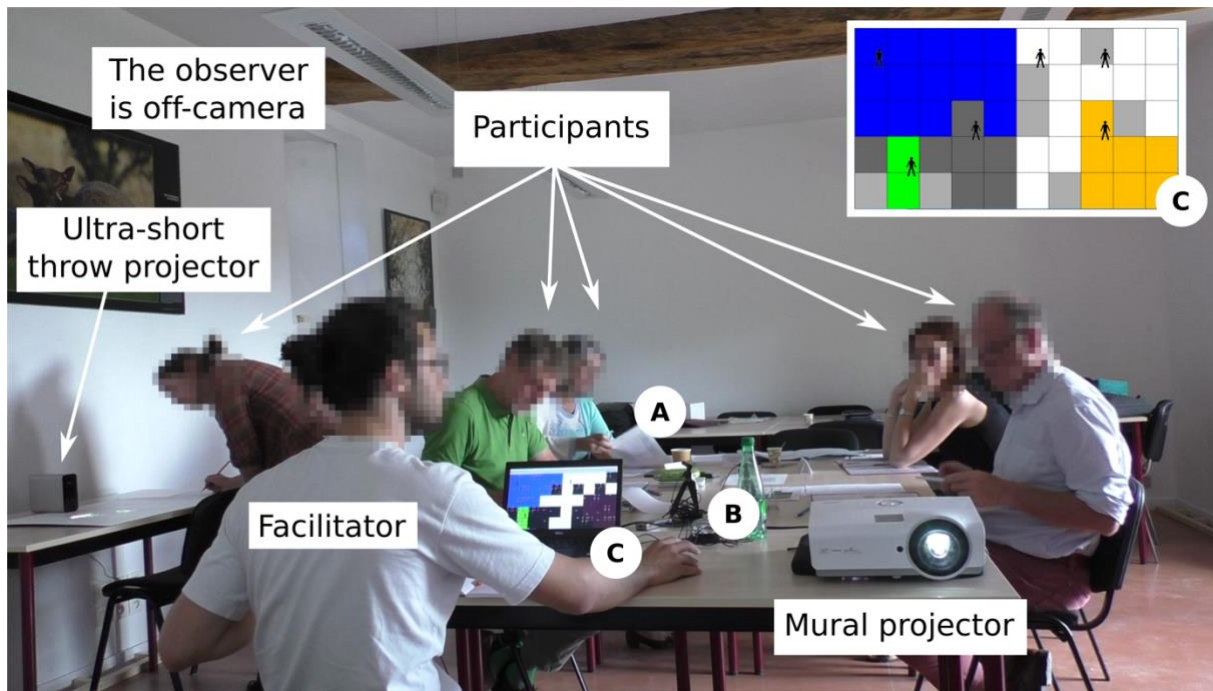
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337 3.2.2. Computerizing participants' decisions and their effects on the agent-based model

338

339 Attendees can choose between many actions specific to forest management such as tree
 340 harvesting or hunting. During a participatory simulation, players have two information sources
 341 at their disposal to reach their objectives. First, a personal booklet lists the different silvicultural
 342 actions (Fig. 2) and their consequences on social, ecological, and economic indicators
 343 (inhabitants' satisfaction; soil fertility, water quality, grazing rates; personal budget). Second,
 344 two maps of the simulation environment are projected (Fig. 4). One is projected onto a vertical
 345 screen; it shows the 50 plots of the simulation, with a background map of the property

346 boundaries and a forest inventory of each plot's forest (number of trees per hectare, by species
347 and diameter). The second map is displayed horizontally on a table close to the players using
348 an ultra-short throw projector. It is made available at the request of participants to show them
349 any information of interest. For instance, the protected area manager can ask for the location of
350 plots eligible for the conservation program.
351



352
353 **Figure 4. Set-up of a participatory simulation of *Foster Forest*.** A: The participant reads the
354 explanatory booklet. B: Sound recording system, supplemented by a video recording system
355 from which the photograph was taken. C: Background map of the simulation with colored
356 properties. This main map is duplicated by a vertical projection onto the wall. Appendix D
357 further details the visual interface.

358
359 As soon as they decide on their forest operations, the participants go to the facilitator who
360 implements their decisions on the computer.

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

366 Participants then give instructions for the forest operations to take place on every plot of the
367 estate that they possess or manage: voluntary or paid participation in the fake “PFSC”

368 certification system – an *ad hoc* mixture of the Program for the Endorsement of Forest
369 Certification (PEFC) and the Forest Stewardship Council (FSC) –, number of trees harvested
370 (detailed by species and diameters), slash removal, and plantation if needed. The foresters’
371 budgets change directly in line with the implemented silvicultural actions in order to reflect the
372 costs (workforce wages, nursery seedlings, skidding, taxes, etc.) and benefits (timber revenues)
373 of the forestry operations. Ecological indicators also evolve in relation to the participants’
374 silvicultural choices: soil fertility decreases in the case of slash removal, clearcutting of an
375 entire plot, or softwood planting, although it increases when nothing happens (Appendix C).
376 Slash removal also lessens the belowground carbon stock (Appendix C). Water quality,
377 measured at the whole forest scale, depends on the mean soil fertility, the proportion of
378 coniferous species, and the number of clearcut plots (Appendix C).

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

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

389

390 3.3. *Testing the calibration and scenarios*

391

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

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

401 Second, the test sessions emphasized the usefulness of pre-coded functions in the ABM,
402 which were not communicated to participants, so as to facilitate a *free-play* mode permitting

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

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

412

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

414

415 *4.1. Temporal organization of the participatory simulations*

416

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

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

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

431 The simulation only begins after completing these two initial steps. It consists of three to
432 five similar steps, each corresponding to a 10-year period (step 1: 2020-2029, step 2: 2030-
433 2039, etc.). Each step starts with announcements concerning decadal projections for climate
434 change as well as timber and carbon prices. The players can then freely talk with each other and
435 approach the facilitator at any time to implement their forest management decisions, with no
436 predefined order for taking turns. A ringtone announces the end of the action period and the
437 launch of the computerized updating of the spatial, social, and physical entities. At this point,

438 the facilitator spends 10 min providing a collective overview of the forest, property, and stand
439 parameters (see Fig. 2), and communicates the climate record of the last decade. The end of a
440 step is also the appropriate time for participants to ask for the organization of a meeting on any
441 issue of importance to them – for instance, a meeting was once requested by a mayor to
442 elaborate a collective strategy to reinforce the social acceptability of tree removal. Overall, each
443 step lasts 20 to 40 min, except for the first one (1 h) to account for the learning phase.

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

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

461 462 *4.2. Spatial organization of the participatory simulations*

463
464 Seat distribution is unchanged throughout the simulations in order to facilitate the
465 subsequent video comparison of strategies developed by different participants with the same
466 role. The spatial configuration of seats also mimics real-world patterns of interactions between
467 participants. For instance, it is legally embedded that the National Forests Office must provide
468 technical assistance to elected officials of municipalities that own communal forests; hence, the
469 public forester and the mayor are always placed next to each other.

470 When seated, all participants can see the vertical projection of the main map. However, they
471 must move to see the horizontal screen, most often placed on a smaller support isolated from
472 the central table, while the economic prices are pinned on a wall. This enables us to refine our

473 observations regarding the information searched by the participants (who they are, when they
474 need the information, etc.). Participants can also move throughout the simulation space to
475 communicate with each other or with the facilitator. The computer on which the facilitator
476 inputs the players' decisions is located on one side of the room. The observer does not interact
477 with the participants.

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

480

481 **5. Results from nine study cases**

482

483 *5.1. Study cases analysis*

484

485 5.1.1. Presentation of the study cases

486

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

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

502

503 5.1.2. Methodological approach

504

505 The analysis was based on the observer's notes, the questionnaires, and the audio and video
506 content collected during the workshops. Any moments of interest (e.g., discussions,
507 negotiations) identified in the simulations were transcribed, as were all the debriefing sessions.
508 Audio recordings and written transcriptions were analyzed using Sonal, an encoder software

509 that conducts audio-textual synchronization (Nicolas, 2013). Sonal allows for thematic and
 510 statistic discourse studies such as topic occurrences and co-occurrences (e.g., “climate change”
 511 and/or “timber production”). For our analysis, we coded the informative segments of each
 512 participatory simulation with thematic tags. These tags related to the components of the
 513 conceptual framework (ES providers and beneficiaries, ecosystem features, ES, as detailed in
 514 Fig. 1), climate change features, and *Foster Forest* as a participatory simulation (Table 1).
 515

516 **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
Interaction between ES stakeholders	Hiking, bike riding, etc. Carbon storage Intermediary bodies (natural regional parks, etc.) Contractualization, public policies, collective action	
Adaptive change in forest management	Forest management approach, <i>sensu</i> 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

517

518

519 5.2. *Lessons learnt from the study cases*

520

521 5.2.1. Climate change adaptation: Technical, timber-focused, and of secondary
522 importance

523

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

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

549 The search for adapted species was frequently shared by both public and private foresters,
550 but some foresters considered that achieving such outcomes would take decades and that
551 monospecific stands would not be resilient to parasite outbreaks. Hence, they favored risk-
552 dilution through species mixtures. Even though this adaptation strategy was tailored to the stand

553 scale, it was tree-centered, as virtually no forester spoke of forest fauna, flora, or fungi – the
554 only mention of soil fungi was made by a naturalist not trained in forestry.

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

559

560 5.2.2. Socio-economic changes in the provision of ecosystem services

561

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

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

586 In the three workshops, the design of the payment for carbon storage allowed us to clearly
587 distinguish between ES providers. Some private foresters adopted an economic approach by

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

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

611 612 5.2.3. Participants’ feedback on *Foster Forest* 613

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

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

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

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

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

657

658 **6. Conclusion**

659

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

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

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

688

689

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703
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924
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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 <i>ODD+D Model description</i>	
D) Overview	I.i Purpose	Research question incl. test of hypothesis, system understanding, theory development, quantitative predictions, management or decision support, communication and learning (participatory modeling)	<i>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>	
			<i>Scientists, but it can also be used for educational or awareness-raising purposes by others.</i>	
	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)	<i>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>
		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,	<i>Cf. Fig. 2 in the main text.</i>

			vegetation cover, soil type), current land use <u>of collectives</u> : 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	<i>Climate change (see Appendix B), economic variations of the timber market (see Appendix C).</i>
		I.ii.d If applicable, how is space included in the model?	Not included, spatial implicit, spatial explicit, georeferenced (GIS)	<i>Spatial explicit, or “stylized” sensu (Le Page and Perrotton, 2017).</i>
		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	<i>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>
	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	<u><i>Each timestep begins with players’ decisions.</i></u> 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. <u><i>Each timestep follows with the computerized update of:</i></u> 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?		<i>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.</i>

		II.i.b On what assumptions is/are the agents' decision model(s) based?	<p><u>Established theories</u> (micro-economic models: homo oeconomicus, full / bounded rationality; cognitive models: social psychology, mental models; space-theory based models)</p> <p><u>real-world observations</u> (mechanistic explanations / process-based understanding available; black-box, use of heuristics, statistical regression methods)</p> <p><u>ad-hoc rules</u> (dummy rules, e.g. constancy assumption)</p> <p><u>combinations</u> of theory and observations</p>	<i>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).</i>
		II.i.c Why is a/are certain decision model(s) chosen?	Data (non-) availability, pattern-oriented modeling, reference to other studies, theoretical considerations	<i>Lack of available data on how adaptations occur in the field.</i>
		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	<i>Data derive from previous field work (Fouqueray et al., 2020). Other data sources are described in Appendices A and B.</i>
		II.i.e At which level of aggregation were the data available?	Household / individual level, group level	<i>Individual level.</i>
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	<i>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.</i>
		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)	<i>Agents pursue personal objectives fixed in the game and presented during the introductory brief (bounded rationality).</i>
		II.ii.c How do agents make their decisions?	Decision tree, utility function, random choice	<i>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.</i>
		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	<i>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.</i>

	II.ii.e Do social norms or cultural values play a role in the decision-making process?	Cultural norms, trust	<i>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.</i>
	II.ii.f Do spatial aspects play a role in the decision process?	Space-theory based models	<i>Yes. Private foresters tend to group their plots through land transactions.</i>
	II.ii.g Do temporal aspects play a role in the decision process?	Discounting, memory	<i>Yes. Agents have a memory of past climate catastrophes. They bear future impacts of climate change in mind when taking their management decisions.</i>
	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	<i>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.</i>
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	<i>No.</i>
	II.iii.b Is collective learning implemented in the model?	Evolution, genetic algorithms	<i>No.</i>
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?		<i>Exogenous variables: decadal projections of climate conditions and timber prices.</i>
	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	<i>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.)</i>
	II.iv.c What is the spatial scale of sensing?	Local, network, global (whole model space)	<i>Local (properties).</i>
	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.	<i>All mechanisms are described in the participant's role booklet, and all participant receive the same introductory briefing.</i>

	II.iv.e Are costs for cognition and costs for gathering information included in the model?		<i>No.</i>
II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Extrapolation from experience, from spatial observations	<i>Data on decadal climatic and economic conditions.</i>
	II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?		<i>No specific models other than the reasoning abilities of each individual as she/he would implement them in a comparable real-world situation.</i>
	II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	(External) uncertainty, (internal) capability of the agent	<i>External uncertainty.</i>
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)	<i>Indirect interactions (e.g., movement of game, water quality, landscape esthetic value).</i>
	II.vi.b On what do the interactions depend?	Spatial distances (neighborhood), networks, type of agent	<i>Networks.</i>
	II.vi.c If the interactions involve communication, how are such communications represented?	Explicit messages (Matthews et al., 2007)	<i>/</i>
	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	<i>No initial coordination network exists, but it can emerge from participants.</i>
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	<i>No (a private/public foresters distinction has been discarded, since it does not affect individual decisions).</i>
	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)	<i>/</i>
II.viii Heterogeneity	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?	<i>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)</i>
	II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?		<i>No.</i>

	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?		<i>The evolution of soil quality and belowground carbon storage are partly randomized. Initial distribution of tree volumes is partly random.</i>
	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?		<i>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.</i>
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)		<i>A pattern of monospecific or species-mixed forest plots emerge depending on the economic and climatic risk-aversion of the agents.</i>
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	<i>In CORMAS, with SmallTalk language. See also the main text.</i>
		III.i.b Is the model accessible and if so where?	Homepage? (link)	<i>www.fosterforest.fr</i>
	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	<i>Five foresters with the same initial budget but unequal forest properties in terms of surface and trees distribution.</i>
		III.ii.b Is initialization always the same, or is it allowed to vary among simulations?		<i>Initialization is always the same.</i>
		III.ii.c Are the initial values chosen arbitrarily or based on data?	References to data if any, stakeholder choice	<i>Based on data. See the other Appendices.</i>
	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, <u>not</u> : parameter values, initial values of state variables	<i>Yes. See Appendices B and C.</i>
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	<i>For the forest growth model, see Appendix B. For social, ecological, and economic processes, see Appendix C.</i>	
	III.iv.b What are the model parameters, their dimensions and reference values?	Tables of parameters	<i>See Appendices B and C.</i>	
	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	<i>See Appendices B and C.</i>	

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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:

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

(Eq. B.1)

where

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

38

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

40

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

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

50 *Hunting.* Hunting modifies the intensity of grazing by boars or deer. At every step, the participants
 51 select a high, medium or low hunting pressures to be applied on their plots. A high, medium, or low
 52 grazing rate induces the death of 30%, 10%, and 0% of trees of stratum 1, respectively. This outcome is
 53 calibrated by forestry reports and newspapers (FIBOIS Alsace, 2014; Odermatt, 2015; Saint-Andrieux,
 54 1994) and from previous interviews conducted with foresters in the “Grand Est” and “Nouvelle-
 55 Aquitaine” regions (Fouqueray et al., 2020). Death processes are operated before performing a new run
 56 of the ABM.

57 *Soil fertility.* The growth model does not account for growth variation linked to the fertility of the
 58 soil (Eq. B.1.). Soil fertility is only accounted for during the initialization and update of the water quality
 59 indicator. In the ABM, the initial volume of trees located on medium fertility stands is the same for each
 60 category of diameter and species (e.g., every sessile oak of diameter 2 has the same volume). In low

61 fertility stands, this initial volume was modified by a factor randomly chosen from 0.9 to 1, and in high
 62 fertility stands from 1 to 1.1.

63

64 3. Including the effects of climate change

65

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

75

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

	<i>Quercus petraea</i>			<i>Quercus robur</i>			<i>Fagus sylvatica</i>			<i>Pinus sylvestris</i>			<i>Pseudotsuga menziesii</i>		
	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%

77

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

82

83 **4. Model parameters**

84 Eq. B.1. was solved as a system of difference equations using one-tenth of a year as the temporal
85 step (i.e., $\Delta t = 0.1 \text{ year}$). As the virtual length of a round was 10 years in the participatory simulation,
86 100 iterations occurred between 2 rounds. The temporal parameters were first calibrated to fit to an
87 annual reference and then brought back to one-tenth of a year. Similarly, the spatial parameters used in
88 Eq. B.1. were first calibrated at a 1-ha scale and then revised to fit the 5-ha spatial scale used in the
89 participatory simulation.

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

91

92 **Table B.2. Parameters used in the forest growth model and the initialization of the**
 93 ***Foster Forest* agent-based model.**
 94
 95

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		0.00458		
Pinus2	0.0028	h: rate of switchover from strata 2 to strata 3		
Pseudotsuga2	0.0042			
QuercusP2	0.01			
QuercusR2	0.0088			
Fagus3	0.00769			
Pinus3	0			
Pseudotsuga3	h: rate of switchover from strata 3 to strata 4	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		760 in pure stands, 58 in mixed stands	
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	Number of trees of a given species and diameter on a forest plot	300 in pure stands, 3 in mixed stands	ha ⁻¹
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	

(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.

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		0.0167		
Pinus		0.0222		
Pseudotsuga	s: recruitment sensitivity to light interception	0.0182	ha.m ⁻²	Thomas Cordonnier (personal communication) and Mathias et al. (2015)
QuercusP		0.0182		
QuercusR		0.02		
Fagus		0.02		
Pinus		0.0286		
Pseudotsuga	u: growth reduction by asymmetric competition from higher strata	0.0222	ha.m ⁻²	Thomas Cordonnier (personal communication) and Kunstler et al. (2011)
QuercusP		0.0222		
QuercusR		0.025		
Fagus		1.0e-4		
Pinus		0.00143		
Pseudotsuga	z: death increase due to asymmetric competition from higher strata	0.00111	ha.t ⁻¹ .m ⁻²	Mathias et al., 2015
QuercusP		0.00111		
QuercusR		0.00125		

96

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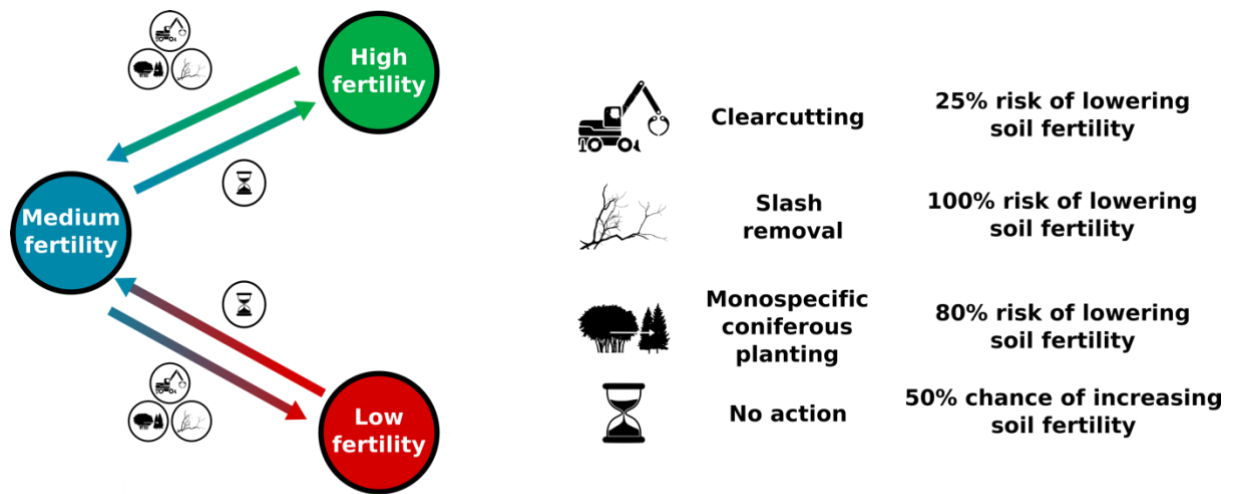
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1 **Appendix C: Consequences of participants' decisions on ecological, social and economic**
 2 **processes**

3
 4
 5 **1. Soil fertility**

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



10
 11 **Fig. C.1. Evolution of a plot's soil fertility.**

12
 13 **2. Water quality**

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

17
$$w_j = \frac{2m_j - 2c_j - q_j}{w_0} \quad (\text{Eq. C.1.})$$

18 where:

- 19 - w_j is the water quality at the beginning of round j ;
 20 - m_j is the proportion of mature trees in the whole forest at the beginning of round j ;
 21 $m_j = \frac{x_3 + x_4}{x_1 + x_2 + x_3 + x_4}$ where x_k is the number of trees of diameter k in the whole forest;
 22 - c_j is the proportion of coniferous trees in the whole forest at the beginning of round j ;

23 $c_j = \frac{x_{3,d} + x_{4,d} + x_{3,e} + x_{4,e}}{x_2 + x_3 + x_4}$ where $x_{k,i}$ is the number of trees of diameter k and species i in the whole
 24 forest (d : *Pinus sylvestris* and e : *Pseudotsuga menziesii*), and x_k is the number of trees of
 25 diameter k in the whole forest;
 26 - q_j is the proportion of the 50 plots with low soil fertility.

27

28

29 **3. Carbon storage and flows**

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

37

38 **4. Inhabitants' satisfaction level**

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

$$43 \quad v = \frac{1 - (p_{pure} + p_{Douglas\ fir})}{p_{tot}} \quad (\text{Eq. C.2.})$$

44 where:

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

50

51

52 **5. Initialization of social and ecological parameters**

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

55
 56 **Table C.1. Ecological and social parameters used in *Foster Forest*.**
 57

Class	Attribute	Value	Unit	Reference
Forester managers	Budget	0	/	Fixed by authors
<i>Foster Forest</i> ABM	Number of plots	50	/	Fixed by authors
<i>Foster Forest</i> ABM	Inhabitants' satisfaction level	0.5	/	Fixed by authors
<i>Foster Forest</i> 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 <i>Pseudotsuga</i> stand, 96.0 in the presence of <i>Pinus</i> , 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

58
 59
 60
 61
 62 **6. Economic parameters**

63
 64 *6.1. Timber and carbon prices*

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

72

Species	Diameter	Initial prices	Round 2	Round 3	Round 4	Round 5
		2020-2029	2030-2040	2040-2050	2050-2060	2060-2070
Sessile oak (€/m ³)	1	14				
	2	14				
	3	62	-20%	+50%	-10%	-7%
	4	223				
Pedonculate oak (€/m ³)	1	14				
	2	14				
	3	62	-20%	+50%	-10%	-7%
	4	223				
Beech (€/m ³)	1	15				
	2	21				
	3	41	0%	-20%	+50%	-60%
	4	41				
Pine (€/m ³)	1	11				
	2	28				
	3	28	0%	0%	+20%	-10%
	4	28				
Douglas fir (€/m ³)	1	30				
	2	30				
	3	40	0%	0%	+20%	-10%
	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%

73

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

77

78 6.2. Land sales

79
 80 Land sales occur at the end of a round. Participants state their potential interest in selling or buying
 81 forest plots. If an agreement is reached between two players, then the landownership changes and the
 82 financial transfers occurs. Participants can rely on the land prices shown in Table C.4., inspired from
 83 Société Forestière and Terres d'Europe-Scafr (2018).

84

	Plot(s) number	Value (€/plot)
<i>Land price</i> <i>(private plots only, public plots are not transferable)</i>	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)
<i>Additional state taxes and notary costs</i>	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%

85

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

87

88

89

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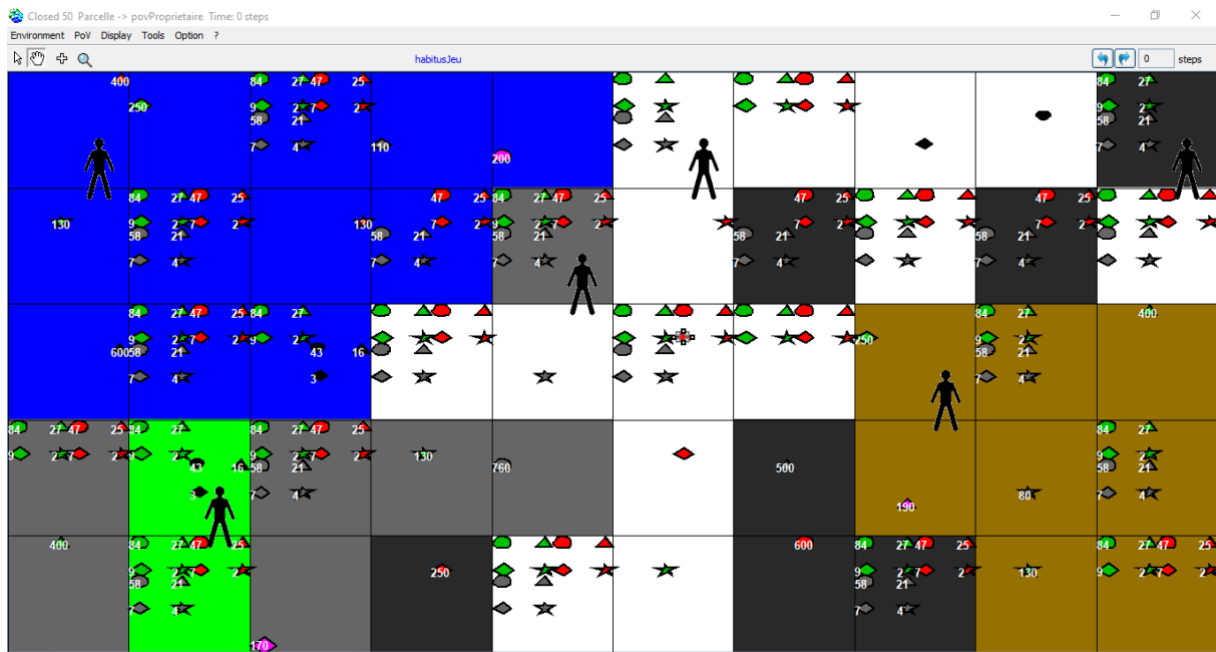
1 **Appendix D: Visual interfaces used in *Foster Forest***

2

3 **1. Interface displaying plots' features (used anytime)**

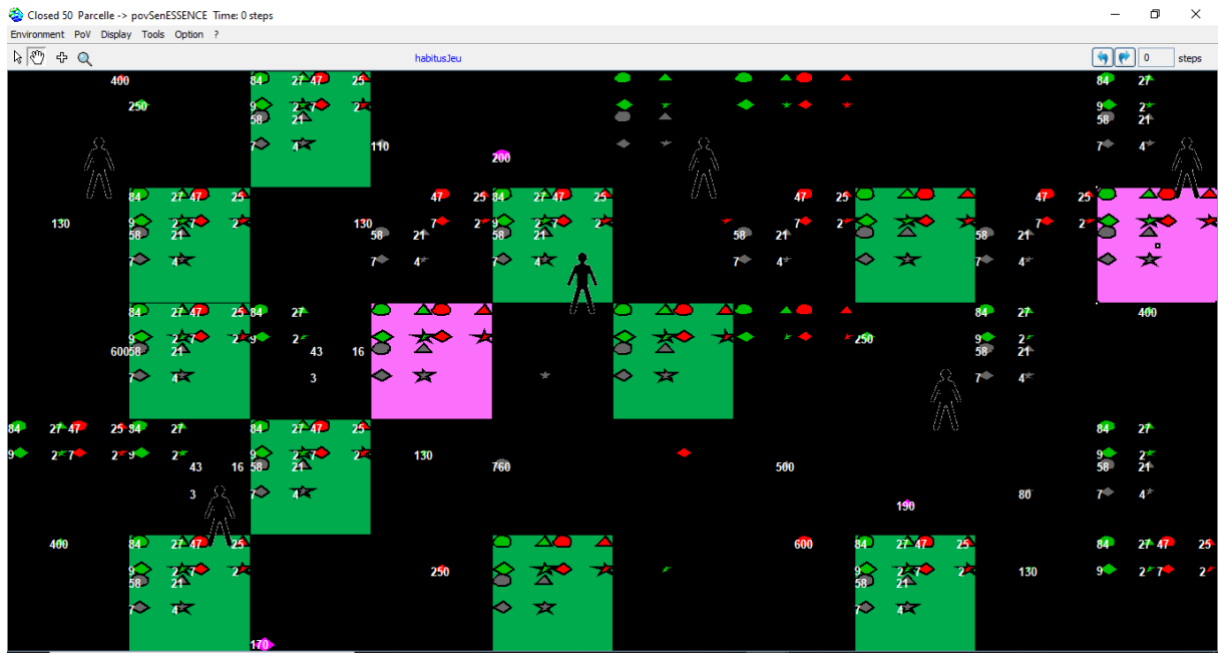
4 The projection of the forest map on a wall can display different features, such as plot ownership, soil
5 quality, eligibility to a conservation program, *etc.* Plot colors vary depending on the variable considered
6 (Fig. D.1.).

7



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

18

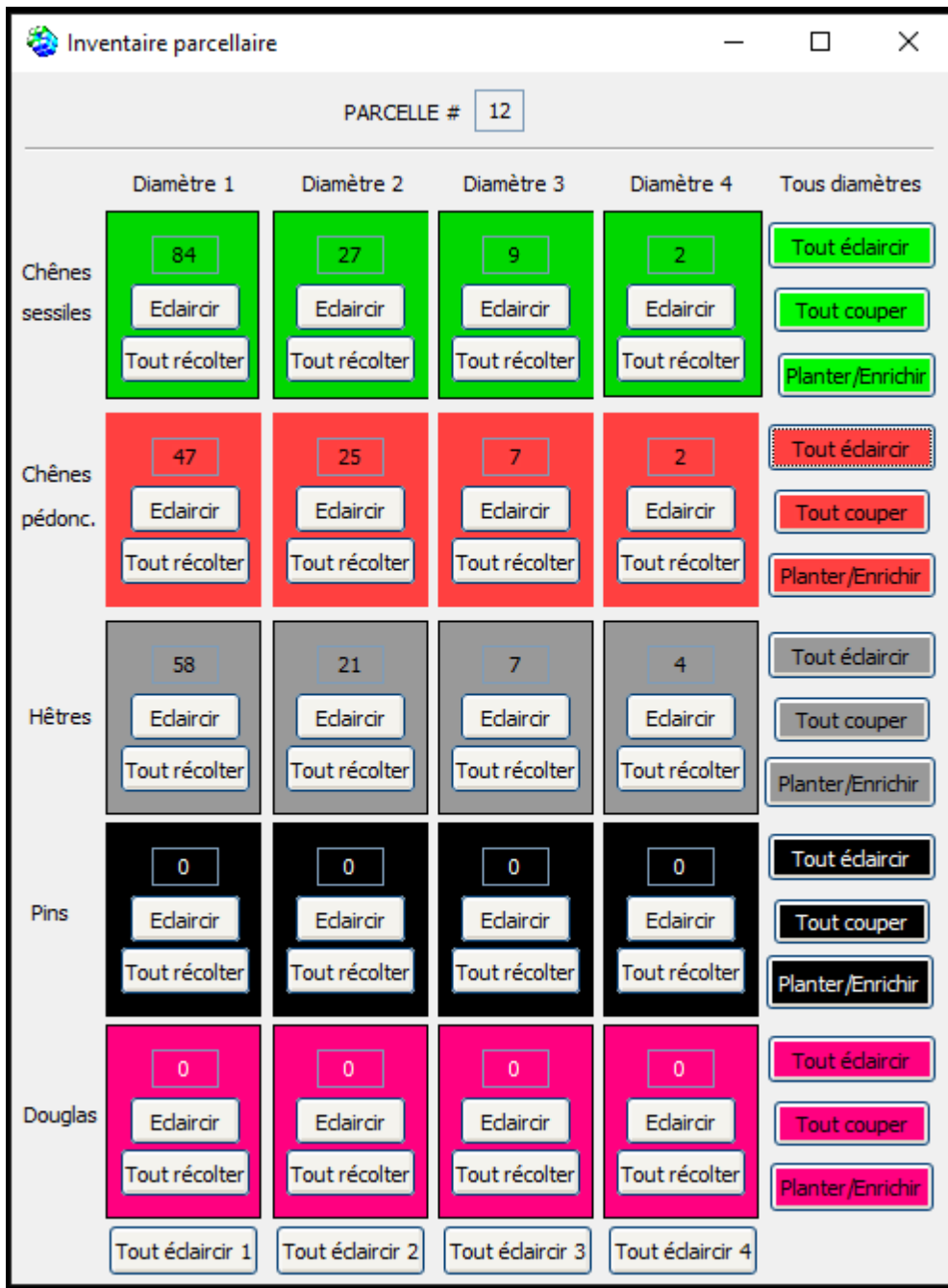
19 **2. Interface for the implementation of players' decisions (during a round)**

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

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

26

27



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

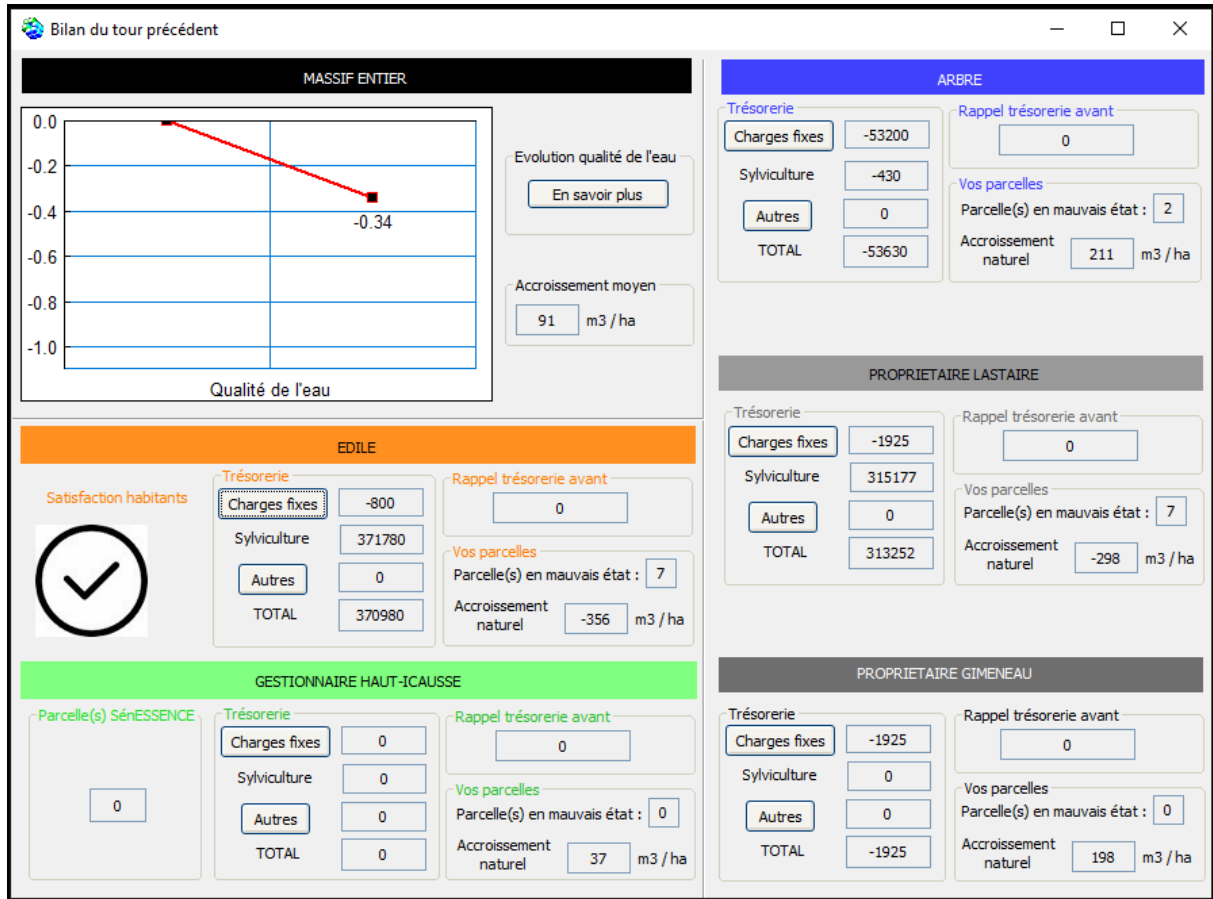
31

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

34 General and individual indicators evolve depending on the actions undertaken at the previous round
 35 (Fig.D.3). Feedback loops act on the evolution of many indicators. For instance, if a high level of hunting

36 pressure was applied to a property, but not to the neighboring properties, its overgrazing damages due
37 to hunt game will still be high.

38



39

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