

From Local Actors to Leaf Protectors: A Companion Modeling Approach for Rethinking Tree Management and Protection Measures in Senegal's Groundnut Basin

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Abstract

How can a participatory simulation model contribute to understanding the socio-ecological dynamics and fostering innovative strategies for sustainable management of trees, crops, and pastoralism in the peanut basin?

In the agro-pastoral zones, the Sahelian ecosystems have undergone significant degradation, characterized by a reduction in tree cover, as a consequence of the droughts in the 1960s and 1990s. The peanut basin stands out for its positive interrelationships between trees, crops, and pastoralism. However, the regeneration of the *Faidherbia* park has declined since the major droughts. Through collaborative efforts with agro-pastoral farmers, we have developed a simulation model – The SAFIRe model : Simulation of Agents for Fertility, Integrated Energy, Food security, and Reforestation – that aims to unravel the complex social and ecological dynamics at play and explore potential strategies in partnership with local communities.

By exploring the results of the model co-designed with local stakeholders, we have identified more effective management strategies, as per the request of the local actors. However, more importantly, we have collectively questioned the conditions for improving tree cover and the viability

of the socio-ecosystem, particularly in relation to the demand for firewood and local cereal for sustenance. This has prompted the stakeholders to engage in community-wide discussions and transform agro-pastoralists into leaf protectors.

keyword : Complex system, agent based model, Companion Modeling, Companion Exploration, community based resource management, Senegal

1 Introduction

The Sahelian region has witnessed a series of devastating droughts from the 1960s to the 1990s, leading to substantial ecosystem degradation, particularly through a significant reduction in tree cover (Mbow et al. 2015). This loss has adversely affected essential ecosystem services, impacting both the population and biodiversity. The severity of this tree cover loss becomes even more alarming given the rapid population growth in the Sahelian region (Cesaro et al. 2023). In a context of scarcity, intensive natural resource utilization by agriculture and livestock further exacerbates land degradation and soil fertility (Tappan et al. 2016).

Ester Boserup (Boserup and Chambers 1965) proposed that declining soil fertility compels farmers to intensify their agricultural practices. Subsequent studies have often focused on this intensification as a primary response to social and agricultural phenomena.

Within the DSCATT project (Dynamics of Carbon Sequestration in Soils of Tropical and Temperate Agricultural Systems), participants in Senegal’s living-labs quickly associated soil fertility with the presence of *Faidherbia albida* trees. This insight directed our research towards understanding the significance of trees in the agricultural practices of the Senegalese peanut basin. By examining tree usage and local management practices, we developed the SAFIRE model (Simulation of Agents for Fertility, Integrated Energy, Food Security, and Reforestation). This approach is part of Companion Modeling (ComMod) (Etienne 2014; Barreteau et al. 2003) and Accompanying Exploration (ComExp) (Delay, Chapron, et al. 2020), aiming to collaboratively explore potential futures for the territory.

In the context of sustainable land management, restoration options identified by farmers are closely linked to tree monitoring to mitigate predation risks from neighboring populations, especially in the longstanding conflict between farmers and herders. Two exploration pathways emerged from discussions with local communities: the impact of delegated surveillance to forestry agents and the conditions for tree park development under community-managed surveillance.

We thus explored community-based natural resource conservation solutions, extensively documented since the Rio Summit promoted them (Selfa and Endter-Wada 2008; Maraseni et al. 2019; He et al. 2020). While the influence of different tree management approaches (delegated to forestry services or managed by

the community) has been extensively debated, highlighting the territorial configurations each approach generates, a crucial point was raised. Through our co-constructed agent-based simulation, validated by stakeholders, we demonstrated that herders were often scapegoated for tree loss in the area. As farmers transitioned from manual to plough-based agriculture, they did not have time to adapt their practices to protect young tree saplings.

By employing ComMod and ComExp approaches, we aimed to assist stakeholders in reimagining future scenarios (Jansujwicz et al. 2021) to support desired territorial transformation. Our goal here is to facilitate discussions and enhance stakeholders’ capabilities through companion modeling. By adopting ”Different Modelling Purposes” (Edmonds et al. 2019), we position our intervention within two categories: illustration and social learning (Le Page and Perrotton 2017). We view illustration as a means to discern viable paths by extensively exploring the co-constructed model. These illustrations should remain within a framework of social learning, meaning they are constructed to reflect the shared vision of stakeholders about the world, assuming that they will then be better positioned to leverage the results to transform their system.

2 Materials and Methods

The Rio Summit in 1992 marked a significant turning point in the perception of natural resource management. It contributed to the democratization of community-based management, promoting a shift from an authoritarian vision of resource management to more integrated approaches (Delay, Ka, et al. 2022). This evolution recognized the importance of actively involving local stakeholders in decision-making and the management of their natural environments. However, integrating communities into resource management processes has introduced complex challenges, particularly regarding the co-construction of common representations and understandings of these environments.

Integrating heterogeneous actors within collectives to co-construct models and simulations has emerged as an innovative response to these challenges. Fully aligned with the philosophy of companion modeling, this approach has given rise to novel methods. In our work, we facilitated workshops aimed at developing an anticipatory method we named ACARDI (Perrotton et al. 2021). This method relies on close collaboration between researchers and local actors, emphasizing the co-construction of models and simulations to anticipate territorial changes. At the end of the process, we established the first Living Lab of the Niakhar observatory.

After conducting participatory workshops in Dioline, actively involving local stakeholders, we identified several specific aspirations and concerns of the population regarding their territory. Among these, the aspiration for the ”return of fauna and flora” particularly caught our attention. To explore this aspiration more thoroughly, we combined an anthropological approach with the co-construction of a simulation model. This section focuses on our approach and methodology aimed at bringing this aspiration to life, combining socio-cultural

121 aspects and modeling tools for a holistic understanding.

122 **2.1 Modelling for Empowerment - An Anthropological Ap-** 123 **proach to Participatory Model Co-construction**

124 The implementation of the ACARDI workshops marked a crucial phase of our
125 research, characterized by a three-month immersion in Diohine. This immer-
126 sion extended beyond workshop discussions, enabling an in-depth information
127 collection process through interviews and participant observation. This field-
128 work was essential for gaining a nuanced understanding of the local population's
129 aspirations and concerns regarding territorial management.

130 Through these interviews, focus groupes and participant observation, a pro-
131 cess of developing conceptual models was initiated, gradually evolving into the
132 creation of an agent-based computational model. The co-construction of these
133 models was a collaborative and iterative approach, actively involving the stake-
134 holders of the Diohine Living Lab. Local actors played a key role in discussing,
135 evaluating, and validating each aspect of the model, thereby ensuring it accu-
136 rately reflected their realities and expectations.

137 Following a thorough validation of the model with local stakeholders, de-
138 scribed as expert validation (Bommel 2009), we began exploring the model
139 using the OpenMole platform (Reuillon et al. 2013). This exploration phase
140 allowed us to simulate various scenarios and gather significant results, which
141 were then presented to the Living Lab participants for feedback and further
142 discussion. To facilitate this crucial step, we developed an interactive interface
143 designed to simplify the manipulation and validation of large amounts of data
144 by the stakeholders, ensuring a smooth and collaborative experience.

145 **2.2 ODD**

146 In this section, we will describe the SAFIRE model (Simulation of Agents for
147 Fertility, Integrated Energy, Food security, and Reforestation) using the ODD
148 (Overview, Design concepts, and Details) framework (Grimm, Berger, Bas-
149 tiansen, et al. 2006; Grimm, Berger, DeAngelis, et al. 2010; Grimm, Railsback,
150 et al. 2020).

151 **2.2.1 Overview**

152 **Purpose**

153 The peanut basin is facing a loss of soil fertility. Chemical amendments are
154 either unavailable in the area or economically inaccessible for farmers. There-
155 fore, soil fertility depends on two aspects: the presence of livestock in the ter-
156 ritory to maintain year-round manure, and the *Faedherbia albida* trees which
157 play a fundamental role in crop cycles. Indeed, these trees have the unique char-
158 acteristic of shedding their leaves during the growing season and fixing nitrogen
159 from the air into the soil.

The model thus aims to evaluate and explore solutions for managing the Faedherbia park to increase their density. The model focuses on exploring so-called community initiatives.

The objective of this study was co-defined with the participants based on their desire to restore trees and biodiversity. According to their perspective, the decline in tree population is strongly linked to individual practices associated with pastoralism. Thus, the aim was to reassess the functioning of their system, the role of "tree cutters," and the optimization of surveillance by comparing community-based surveillance efforts with centralized surveillance conducted by them and the forestry department.

Throughout the study, we also examined the role of farmers and agro-pastoralists in the disappearance of trees. It was observed that young tree seedlings are no longer marked and destroyed by animal-drawn tools.

Entities, state variables and scales

The entities in the model are relatively numerous: some are static (trees, plots, and village), while others are in motion (shepherds, farmers, woodcutters, and overseers).

patches : nbarbresici: Number of trees present on this patch; arbre-ici: Indicates if there is a tree on this patch (reference to a specific tree); tree-influence: Influence of the tree on this patch (can represent aspects like shade, nutrients affected by the tree, etc.); under-tree: (TRUE/FALSE) Indicates if the patch is under a tree; culture: Type of crop on this patch (can be millet or groundnut); en-culture: Indicates if the patch is currently used for crops; rendement-mil-g: Yield of millet on the patch in terms of grains (to be calibrated later); rendement-mil-p: Yield of millet on the patch in terms of bundles; rendement-groundnuts-g: Yield of groundnuts on the patch in terms of grains; rendement-groundnuts-p: Yield of groundnuts on the patch in terms of bundles; id-parcelle: Identifies the parcel, allowing the structure of the parcels to be maintained during rotation; pas-rotation: Tracks parcels that have not yet rotated (system of +1); rotation: (TRUE/FALSE) Indicates if the parcel has already undergone rotation; champ-brousse: Indicates if the patch is in bushland; zoné: (TRUE/FALSE) Indicates if the patch is used for defining fallow zones; zone: Indicates to which fallow rotation zone the patch belongs (there are 3 zones for fallow rotation).

Trees : proche-village: Likely unnecessary variable (trees in villages are also pruned); nb-coupes: Number of cuts; nb-jour-coupe: Number of cutting days; age-tree: Age of the tree. Trees have also a subclass Saplings composed by age: Age in days ; signalé: Reported; rna-coupe: Cut in RNA.

farmers : id-agri: Links to the farmer's unique parcel; engagé: TRUE/FALSE engagement in the Assisted natural regeneration (RNA in fr); interet-RNA: Interest in the RNA; jour-champ: Days spent in the field; nb-ha-a: Number of hectares allocated; stock-mil: Stock of millet; idMyBerger: Identifier of the associated shepherd; nb-patches: Number of patches; mon-chp-RNA: Field in the RNA.

206 hearder : troupeau-nourri: does the herd have enough to eat, currently
 207 TRUE/FALSE; arbre-choisi: tree chosen to be cut and fed to animals as fodder
 208 ; nb-têtes: herd size for the shepherd ; nb-ha-b: Between 3.8 (newly settled,
 209 11%) and 5.5 (89% of the population); stock-fourrage: Forage stock; idAgri:
 210 Identifier of my reference farmer.

211 woodcutters : attrape: Captured (TRUE/FALSE); nb-attrape: Number
 212 time he was captured; jours-peur: Days of fear after capuration; en-coupe:
 213 Currently cutting.

214 The simulated space, through which the agents interact, represents 100
 215 hectares. It is composed of 1000 spatial entities (patches) with a size of 10 square
 216 meters (resolution). It is exclusively agricultural since the inhabited area of the
 217 village is condensed into a single point. (The areas that are not cultivated, such
 218 as wetlands and pathways, are rare and have not been represented.)

219 The irreducible time step is one day (tick). The various elements of the
 220 system (interactions, etc.) take into account the seasonality that structures
 221 agricultural activities. Every 364 days, a new year begins and the rhythm of
 222 the seasons continues. A second time unit can be considered: the year, which
 223 consists of seasons. Simulations are generally carried out over 23 years. At
 224 the beginning of the simulation, the first 3 years are considered to initialize the
 225 model.

226 **Process overview and scheduling**

227
 228
 229 This section provides an overview of the processes and their scheduling
 230 within the model. The model is composed of several sub-models that simu-
 231 late various aspects of the ecosystem and human activities. Each process is
 232 organized and executed in a specific sequence to reflect the interactions and
 233 dependencies within the system. The following describes repeated procedures
 234 that occur at each time step:

- 235 • Harvest and Crop Management
 - 236 – Harvest and stockpiling: Farmers harvest crops and store them in
 237 their stockpiles.
 - 238 – Effect of machinery on unprotected saplings: Machinery used in the
 239 fields may damage or destroy unprotected saplings.
 - 240 – Crop rotation: Farmers rotate crops between different fields to main-
 241 tain soil fertility and reduce pest buildup.
- 242 • Tree Growth and Reproduction
 - 243 – Sprouting: New saplings sprout around mature trees, influenced by
 244 tree density and environmental conditions.
 - 245 – Sapling growth: Saplings grow over time, with growth rates depen-
 246 dent on available resources and environmental factors.

- 247 – Aging and death of trees: Trees age and may eventually die due to
248 old age, disease, or other environmental factors.
- 249 • Livestock Feeding and Forage Use of Acacias
- 250 – Feeding livestock with straw: Shepherds feed their livestock with
251 straw collected from the fields.
- 252 – Tree cutting: Trees are cut down for forage or other uses by the
253 shepherds.
- 254 – Livestock in fallow land and cutting of saplings: Livestock graze in
255 fallow lands, and shepherds may cut down saplings to manage the
256 land.
- 257 • Cutting of Saplings by Woodcutters
- 258 – Detection of saplings: Woodcutters search for and identify saplings
259 that can be cut.
- 260 – Cutting of saplings: Once identified, saplings are cut by the wood-
261 cutters for use as firewood or other purposes.
- 262 • Farmer Engagement
- 263 – Participation in meetings: Farmers participate in community meet-
264 ings to discuss agricultural practices and share knowledge.
- 265 – Observing the success of neighbors: Farmers observe the practices
266 and successes of their neighbors to learn and adapt.
- 267 – Social interaction and motivation: Social interactions among farmers
268 influence their motivation and engagement in community activities.
- 269 – Protection of saplings: Farmers take actions to protect saplings from
270 damage by livestock or machinery.
- 271 • Surveillance
- 272 – Surveillance and presence of farmers in the fields (generalized com-
273 munity surveillance): Farmers patrol their fields and monitor for any
274 issues such as pests or unauthorized grazing.
- 275 – Delegated community surveillance: Specific individuals or groups are
276 assigned the task of community surveillance to ensure all fields are
277 monitored effectively.

278 2.2.2 Design Concepts

279 Basic principles

280
281 In their paper (Roupsard et al. 2020), a link was established between the
282 presence of *Faidherbia albida* trees and the improvement of crop yields in the
283 region. We have extended this work to calibrate the model on the relationship

between these trees and cultivated plants. By engaging with stakeholders on their interactions with plants through food and livestock, we aimed to socially address the paradox of the non-renewal of these trees. Given that the area has been well-documented by agronomists since the establishment of the Niakhar observatory, we were able to collect quantitative data on historical (Pieri 1989; Pelissier 1966) and contemporary (Audouin et al. 2018; Ba et al. 2018) forms of rural organization. This comprehensive documentation facilitated our understanding and analysis of the agricultural systems and social structures within the region. This work primarily involved adopting a systemic approach as identified by the stakeholders during participatory modeling workshops using the ARDI methodology (Etienne et al. 2011; Etienne 2014).

Adaptation

Two agents exhibit adaptive/changing behaviors: the woodcutters and the farmers. The response of the woodcutters to being caught by a sapling protector varies according to the number of times they have been caught previously. Farmers have a score describing their interest in tree protection. This score evolves constantly according to several rules: encountering another engaged farmer, observing the success of a neighbor’s protection system, participating in meetings, etc.

Emergence

There are several intriguing elements to examine, such as the emergence at the model level and the enhanced understanding of social and ecological interrelationships and solidarity among the actors. The model emphasizes the significant impact of agriculture (likely due to the introduction of plow-based farming) on the destruction of *Faidherbia albida* saplings (weak emergence). Moreover, a strong emergence is observed when agents are permitted to organize on a community level, as neighbors gradually engage each other in sustaining interest in assisted tree regeneration.

Highlighting potential long-term trajectories to reach acceptable production volumes should be considered both from the viewpoint of weak emergence within the model, due to its mechanistic processes, and strong emergence, as it drives participants to actively engage and commit to the theme beyond the facilitation process.

Sensing

The patches within the action radius of the trees will yield more. Agents are capable of perceiving the farmers around them. Shepherds will not cut young saplings if there is a concerned farmer nearby, and the same applies to woodcutters. Farmers, in turn, perceive their neighbors and will interact with them if they have adjacent fields. Through these interactions, they discuss assisted natural regeneration (ANR) to persuade each other to adopt this practice.

Interaction

The interaction between agents is direct. Woodcutters interact directly with the saplings by cutting them down. Similarly, shepherds interact directly with the trees by utilizing them for forage. Farmers and supervisors also have direct interactions with woodcutters by stopping them from cutting the saplings. Additionally, farmers destroy young saplings that are not protected.

- **Woodcutters and Saplings:** Woodcutters seek out saplings and cut them down for use as firewood or other purposes. This direct interaction reduces the number of saplings in the environment.
- **Shepherds and Trees:** Shepherds interact with trees by feeding their livestock with tree foliage or cutting down trees for forage. This direct interaction affects the tree population and influences the availability of forage resources.
- **Farmers and Woodcutters:** Farmers interact with woodcutters by attempting to stop them from cutting saplings. When farmers encounter woodcutters in the field, they may intervene to protect the saplings.
- **Supervisors and Woodcutters:** Supervisors, acting as protectors, also interact directly with woodcutters. They monitor the fields and stop woodcutters from cutting down saplings to ensure the protection of young trees.
- **Farmers and Unprotected Saplings:** Farmers destroy young saplings that are not protected. This interaction occurs when farmers are working in their fields and come across unprotected saplings, which they remove to prevent interference with their crops.

Stochasticity

Many events in the model rely on stochasticity since they are probabilistic. Probability is often used as a frequency measure. This is the case for the movements of farmers in their fields and the probability that farmers will discuss the RNA (Assisted natural regeneration) with each other.

Stochasticity is used to represent uncertainty, particularly concerning whether supervisors catch woodcutters. Since supervisors do not spend the entire day in a single field, they may visit a field without encountering the woodcutter.

Finally, randomness is used to create variability in initial conditions. This is the case for the number of heads in different herds, which vary in size, and for the initial age of each tree, resulting in trees of varying ages.

- **Partial Randomness as Uncertainty**

- **Farmer Movements:** The movements of farmers within their fields are determined randomly. This means that their location at any given

time is based on a probability distribution, ensuring variability in their positions.

- Discussions about RNA: The likelihood that farmers will engage in discussions about the RNA is also probabilistic. This frequency-based probability allows for random interactions among farmers, influencing their engagement with the RNA.

- Supervisors and Woodcutters: The uncertainty in supervisors catching woodcutters is modeled using partial randomness. Supervisors patrol fields but may not always encounter woodcutters due to the random nature of their patrol routes and the woodcutters' activities.

- Randomness for Initial Variability

- Herd Sizes: The initial number of heads in each herd is determined randomly, resulting in herds of varying sizes. This introduces variability into the model, reflecting real-world differences in herd sizes.

- Tree Ages: The initial age of each tree is assigned randomly, creating a population of trees with a range of ages. This variability in tree ages ensures a more realistic representation of a forest with trees at different stages of growth.

Collective actions

Collective forms emerge with the engagement of farmers in the protection of saplings. The larger the group of engaged farmers, the more likely it is for others to join, and the more assured the group's longevity.

- Farmer Engagement: As farmers begin to engage in sapling protection, they form groups that work collectively towards this goal.

- Group Growth: The probability of additional farmers joining the group increases with the group's size. This creates a positive feedback loop where the more farmers are engaged, the more likely it is for others to join.

- Group Longevity: The sustainability of the group is enhanced as it grows. A larger group of engaged farmers is more resilient and capable of maintaining their collective efforts over time.

Observation

We will monitor several metrics:

- Millet and Groundnut Production: This indicator tracks the total production of millet and groundnut in the simulation. It helps assess the agricultural output and food security within the modeled environment.

- 409 • Number of Trees at Each Development Stage: This metric measures the
410 number of trees at various stages of development, such as saplings, young
411 trees, and mature trees. It provides insight into the growth dynamics and
412 regeneration of the forest.
- 413 • Number of Trees Destroyed by Each Type of Agent: This indicator counts
414 the number of trees destroyed by different agents, such as farmers, wood-
415 cutters, and livestock. It helps understand the impact of various human
416 and animal activities on the forest.
- 417 • Volume of Wood Cut for Cooking: This metric tracks the amount of wood
418 harvested specifically for cooking purposes. It helps assess the pressure on
419 forest resources for domestic energy needs.
- 420 • Age of Each Tree Sapling: This indicator measures the age of each sapling
421 in the simulation. It provides information on the regeneration rate and
422 the survival of young trees.
- 423 • Number of Farmers Engaged in the RNA: This metric tracks the num-
424 ber of farmers actively participating in the National Agricultural Network
425 (RNA). It helps evaluate the level of community involvement and engage-
426 ment in agricultural and environmental initiatives.
- 427

428 2.2.3 Details

429 Initialization

430 At initialization, the environment is generated with the following steps:

- 431 • Generation of Parcels and Crops: The landscape is divided into parcels,
432 each designated for specific types of crops. This step sets up the agricul-
433 tural fields and assigns crop types to each parcel.
- 434 • Generation of Trees and Their Fertilizing Effects: Trees are distributed
435 throughout the environment, considering their effects on soil fertility. Trees
436 influence the nutrient levels of the patches they occupy, enhancing soil
437 quality in their vicinity.
- 438 • Generation of Human Agents: Human agents, including shepherds, wood-
439 cutters, farmers, and supervisors, are created and placed in the environ-
440 ment. Each agent type has specific roles and behaviors that contribute to
441 the model's dynamics.
- 442 • Generation of the Village: The village is established as a central loca-
443 tion where human agents reside. This step involves setting up the village
444 infrastructure and assigning homes to the agents.

445 Input data

446

447 We dont use input data.

448

449 **Submodels**

450

451 **2.3 Statistical Analysis and our Companion Modeling ap-** 452 **proch**

453 Our work is grounded in the approach of companion modeling (Barreteau et al.
454 2003). However, we aim to address the pressing need for model exploration.
455 This entails combining and hybridizing elements that are rarely integrated: ex-
456 ploring the model alongside the stakeholders. To achieve this, we employed
457 traditional agent-based modeling tools and made a concerted effort to conduct
458 these analyses with the farmers of the peanut basin, engaging them in discus-
459 sions about the exploration results. We performed a sensitivity analysis and
460 utilized the "pattern space exploration" method to produce results reflecting
461 the range of possible long-term scenarios. These results were then discussed
462 with the stakeholders to ensure a comprehensive understanding and validation.

463 **2.3.1 Sensitivity analysis : saltelli method**

464 Sensitivity analysis comprises a range of techniques that assess how a model
465 responds to variations in its input parameters. These statistical methods aim
466 to quantify the extent to which changes in the inputs influence the variability
467 observed in the outputs. In accordance with the definition provided by Saltelli
468 et al. (2008)(Saltelli 2008), sensitivity analysis determines the "relative impor-
469 tance of each input in determining [output] variability." Consequently, these
470 methods often yield a ranking or ordering of the inputs based on their respec-
471 tive sensitivity levels.

472

473 **2.3.2 Pattern Space Exploration (PSE)**

474 The PSE (Chérel et al. 2015) method, based on genetic algorythme, is specifi-
475 cally designed to comprehensively cover the output space, resulting in its max-
476 imum score in output exploration – e.g. "explore the output's diversity of a
477 model"¹. By exploring the output space (c.f. fig. 1), the PSE method uncovers
478 new patterns, providing insights into the model's sensitivity by examining the
479 corresponding input values. Unlike calibration-based methods, PSE's effective-
480 ness is influenced by the dimensionality of the output space, as it keeps a record
481 of all the covered locations during exploration.

¹<https://openmole.org/PSE.html>, consulté le 5 juin 2023

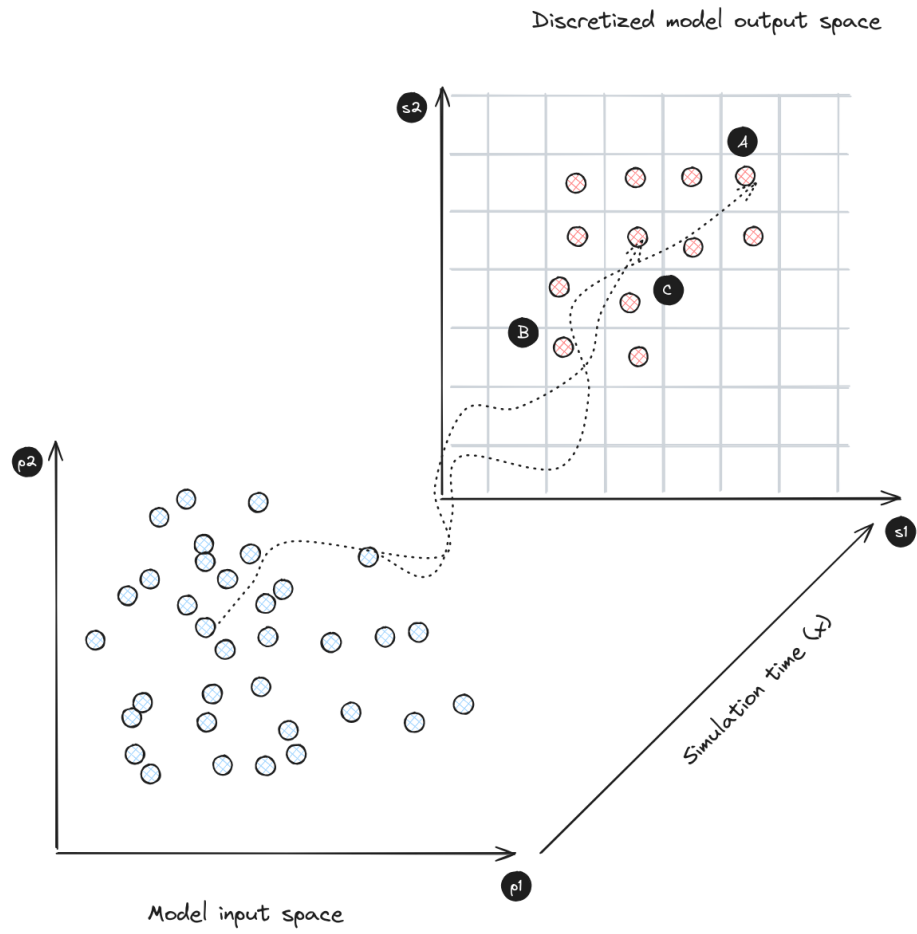


Figure 1: description of how the “pattern space exploration” genetic algorithm works. We see “p1” and “p2” as input parameters, and “s1” and “s2” as output parameters. The algorithm seeks to reach every cell in the grid of “s1” and “s2” to discover the model’s output result domains. A and B and C are outputs of contrasting models

482 In addition, the PSE method usually takes stochasticity into account by
 483 estimating selected models using the median of multiple output values obtained
 484 from model runs. For our purposes, and as we are in a situation where the
 485 results need to be discussed with stakeholders, we have chosen to focus not on
 486 the median, but on the last decille. This means that simulations are retained if
 487 more than 90% of the results converge towards the identified output.

488 The algorithm’s ability to explore a diversity of output forms is extraordi-
 489 narily powerful in the context of companion modeling. Indeed, participants in
 490 co-construction sessions gradually became accustomed to the practice of mod-
 491 eling (Etienne 2014). They developed the ability to interrelate various elements
 492 of the system. However, the strength of agent-based modeling lies in the fact
 493 that they cannot anticipate emergent phenomena. Once the model has gained
 494 sufficient confidence, questioning the group about marginal aspects or uncon-
 495 sidered input parameter sets in the model proves to be extremely fruitful from
 496 the perspectives of emancipation and anticipating unforeseeable situations.

497 **2.3.3 Engaging Stakeholders in Result and Thresholds Discussions**

498 Working with participants on the PSE results enabled us to address the final
 499 conditions and thus the various configurations of the future. To facilitate this,
 500 we organized a feedback workshop during which we presented the simulation
 501 outcomes and discussed their implications for the systems they had described.

502 Subsequently, we took time for collective reflection during which the par-
 503 ticipants collaboratively defined the final conditions that seemed particularly
 504 compelling to them. This interest was formalized around contrasting models.

505 These archetype outputs allowed us to address and clarify situations that
 506 were previously unthinkable (Banos 2010). On figure 1, we can perceive situa-
 507 tions A, B, and C as a series of contrasting scenarios for which we will discuss
 508 with the participants the configurations that have led to these outcomes. This
 509 leads to extremely rich discussions that compel stakeholders to consider these
 510 previously unthinkable situations and to collectively discuss the processes for
 511 satisfying individual needs regarding the collective inputs.

512 **3 Results**

513 The Saltelli analysis allows us to compare two surveillance scenarios, enabling
 514 us to identify the rearrangement of variables that occurs when the surveillance
 515 regime changes.

516 Following this, we conducted a Pattern Space Exploration (PSE) to iden-
 517 tify the simulations that, in the context of community surveillance, increase
 518 the number of trees. This is a nonlinear process with an increase in fertility
 519 correlated with an increase in the number of trees.

3.1 Understanding stackolders Variable Importance via Sensitivity Analysis

We conducted the same analysis twice on different simulation scenarios. First, we performed an analysis on the community surveillance system. The second analysis shifts the workload to a dedicated surveillance system to mimic the functioning of surveillance by a water and forest authority.

Comparing these two analyses allows us to assess the influence of a change in practice on the system's operation and to identify the structural changes they induce.

In a community surveillance scenario, the global sensitivity analysis shows that the probability of discussing the importance of trees plays an extremely significant role in both millet production (0.72) and the total number of trees (0.59) at the end of the simulation (see Table 1).

The frequency of awareness meetings about the benefits of trees has a role, albeit more limited, in the number of trees (0.23) and millet production (0.30). Similarly, the time spent in the fields also affects the number of trees (0.29) and millet production (0.16).

Finally, the probability of reporting a woodcutter when seen impacts the number of trees (0.25) but less so millet production (0.12).

The presence in the bush has little importance on both the number of trees and millet production.

Dans un scenarion dans lequel la surveillance est effectué par un agents des eaux et forêt la dynamique change un peut (c.f. table 2). Dans le mesure ou cette surveillance n'est plus faite par la population.

Le temps au champ, et la probabilité de discuter d'un sujet en lien avec la préservation des arbres sont deux paramètres qui ont une influence relativement forte dans les mêmes ordre de grandeur que le nombre de surveillant. Dans un contexte ou la surveillance n'est pas assuré par la population, la fréquence des réunion, et le probabilité de dénoncé un coupeur n'ont que peut d'influence.

	om_trees	om_stockMil
probaDiscu	0.59	0.72
fréquenceRéu	0.23	0.30
tpsAuChamp	0.29	0.16
probaDenonce	0.25	0.12
nbProTGMax	0.33	0.10
qPrésenceBrousse	0.11	0.04

Table 1: Saltelli sensitivity analysis when surveillance is delegated to the community

	om_trees	om_stockMil
nbProTGMax	0.5	0.3
ok tpsAuChamp	0.29	0.22
ok nbSurveillants	0.20	0.29
ok probaDiscu	0.15	0.27
ok qPrésenceBrousse	0.15	0.10
fréquenceRéu	0.07	0.14
probaDenonce	0.00	0.02

Table 2: Saltelli sensitivity analysis when surveillance is managed transandially

Variables	Range
tpsAuChamp	(0.0, 100.0)
qPrésenceBrousse	(0.0, 1.0)
fréquenceRéu	(1.0, 10.0)
probaDenonce	(0.0, 100.0)
probaDiscu	(1.0, 100.0)
nbProTGMax	(5.0, 50.0)

Table 3: Variation range for PSE parameters in a community surveillance contexte

3.2 Patern Space exploration

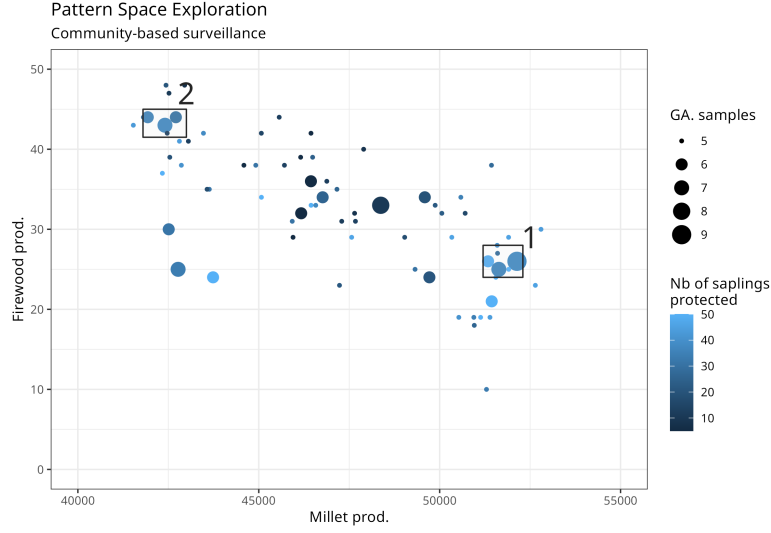
The PSE algorithm discretizes the model output space to systematically explore its diversity. We have configured it to retain only the results achieved in 95% of the simulation cases. The input parameters – shown in Table 3 – are left unrestricted to facilitate this exploration.

On Figure 2, we observe a negative relationship between millet production and firewood production. That is to say, the more we can harvest firewood, the less we can harvest millet.

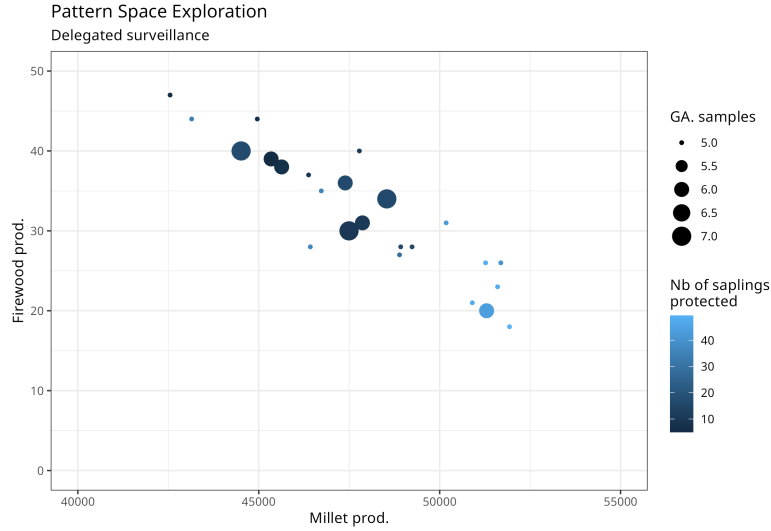
If we then look at the influence of the type of tree surveillance. By comparing the two scenarios, we can see that simulations reaching the numbered spaces 1 and 2 on Figure 2a, representing community surveillance, are less present on Figure 2b, which represents the delegated surveillance scenario. Conversely, on Figure 2b, the model tends to easily reach intermediate situations (large, dark blue points).

The extremes framed in 1 and 2 on Figure 2a are associated with a high number of protected seedlings (*nbProTGMax*). This provides indications on the trajectories of the systems.

In both situations, reducing the harvesting of firewood leads to a higher number of seedlings. In both cases, these situations are reached by simulations where RNA and the diffusion of practices are present in the form of awareness meetings.



(a)



(b)

Figure 2: PSE results for two different management scenarios: (a) community management and (b) management delegated to an external 'operator'. The size of the points (GA. sample) represents the number of times the algorithm reached this space during its evolution. The color of the points represents the number of young tree saplings that were protected. The x-axis denotes the millet production that was achievable, and the y-axis corresponds to the wood fuel extraction for cooking that was realized in the system. In figure (a), the two numbered squares, 1 and 2, represent the two contrasting situations that were discussed.

570 **3.3 Unexpected Yet Attainable: Surprising Results with** 571 **Minimal Calculations**

572 In the context of the co-construction of the simulation model, by integrating
573 some basic indicators, we highlighted a fundamental issue that had never before
574 been raised by the participants of the Living Lab as a major problem. By
575 closely monitoring the total number of trees cut down, whether by herders for
576 livestock, women for firewood, or farmers during their agricultural activities, a
577 surprising trend emerged for the participants (see fig. 3). This analysis revealed
578 that farmers themselves significantly contribute to tree destruction, albeit in
579 a somewhat silent manner. Specifically, this destruction often goes unnoticed
580 because it manifests through the weeding of very young seedlings, carried out
581 by farmers without their full awareness. This result was extensively discussed
582 during the workshop, which allowed for the clarification of farming techniques
583 to ensure that the translation into the model was accurate. This observation
584 challenges some previous perceptions and raises essential questions regarding
585 the management of tree resources within the community.

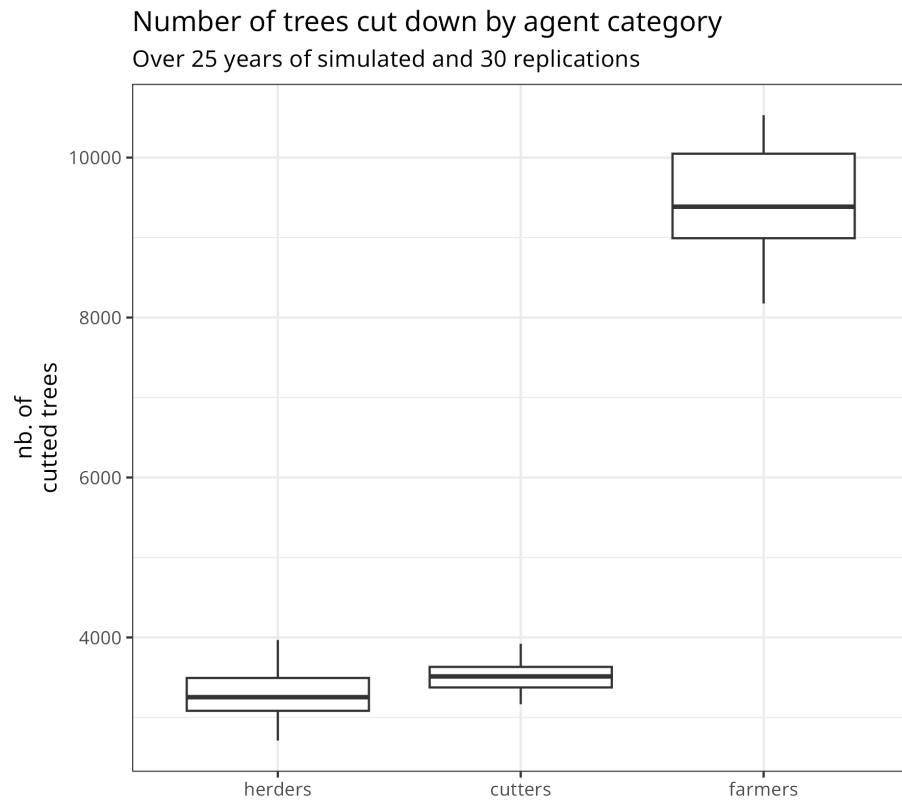


Figure 3: Boxplot showing the total number of trees cut down at the end of the simulation by resource user category. It is evident that farmers are responsible for the highest number of trees removed from the system across all categories. These results are based on 30 replications of the same parameter set.

586 4 Discussion

587 As we outlined in the introduction, our purpose here is to support discussions
588 and the ability of stakeholders to make concerted decisions by using companion
589 modeling (ComMod). By adopting the "Different Modelling Purposes" from
590 (Edmonds et al. 2019), we position our intervention within two categories: il-
591 lustration and social learning (Le Page and Perrotton 2017). Thus, we consider
592 the process as a whole as the outcome (Etienne 2014), leading the involved
593 populations to re-examine their management practices of space and natural re-
594 sources, in order to nurture the socio-spatial relationships that are under stress
595 (Selfa and Endter-Wada 2008).

596 The work we have conducted throughout this process allows us to discuss two
597 dimensions: *i*) the elements of the numerical results directly derived from the
598 model co-constructed with the participants, and *ii*) the transformative impact of
599 the discussions that took place during the process, which have begun to change
600 behaviors.

601 4.1 Discussion of numerical Results

602 Our global sensitivity analysis (tab. 1 and 2) revealed critical insights into the
603 dynamics of community surveillance scenarios. Specifically, we found that the
604 likelihood of community discussions regarding the importance of trees signifi-
605 cantly influences both millet production (with a sensitivity index of 0.72) and
606 the overall number of trees (sensitivity index of 0.59). These results underscore
607 the crucial role of active participation and awareness within the community.
608 They suggest that integrating structured discussions about tree preservation
609 into major life events, like traditional rituals, and daily interactions could en-
610 hance the effectiveness of community-based natural resource management. By
611 formalizing these discussions, communities can better understand and address
612 the ecological and social implications of their traditional and current land use
613 practices.

614
615 In scenarios where surveillance is delegated to forestry agents, the dynamics
616 of resource management shift noticeably. While the time spent in the field and
617 the likelihood of discussions on tree preservation continue to be significant, the
618 introduction of external surveillance personnel brings additional dynamics into
619 play. Our analysis indicates that the presence of these agents decreases the fre-
620 quency of community meetings and the likelihood of reporting illegal activities,
621 suggesting a shift towards a more controlled but potentially less community-
622 involved management system. This shift was evident in our *Pattern Space Ex-*
623 *ploration* (PSE) results (c.f. fig. 2), highlighting changes in community dynam-
624 ics under different surveillance regimes.

625
626 Our PSE analysis has unveiled a notable negative correlation between millet
627 production and firewood harvesting, regardless of the regulatory approach em-
628 ployed. The simulations that reached the extremes of this model output space

629 demonstrated that reducing firewood harvest not only protects more young
630 plants but also significantly boosts millet yields. This finding suggests that
631 policies aimed at reducing wood harvest could simultaneously enhance agricul-
632 tural productivity and biodiversity conservation, offering a dual benefit to the
633 communities involved.

635 4.2 Driving Transformation Through Companion Model- 636 ing

637 Our study has illuminated practical solutions through the use of community
638 surveillance, which has shown improvements in either conservation or agricul-
639 tural productivity goals. However, these benefits require a significant time in-
640 vestment from the community. Effective community surveillance not only de-
641 mands involvement but also a commitment to ongoing dialogues and actions.
642 This investment in time and effort needs to be supported by the community, rec-
643 ognizing the long-term benefits in fostering sustainable practices and enhanced
644 resource management.

645
646 During our research, we identified a critical issue previously unnoticed by
647 participants of the Living Lab : the significant impact of agricultural practices
648 on tree destruction (c.f. fig. 3). This destruction often goes unnoticed as it
649 primarily involves the removal of young saplings during routine weeding, which
650 is less dramatic than the felling of mature trees. The use of ploughs drawn by
651 horses has eased the labor of farmers, yet has inadvertently led to the reduc-
652 tion of young trees. This oversight highlights the need for adapting agricultural
653 practices to mitigate unintended environmental impacts.

654
655 The results of our study profoundly impacted the participants, prompting
656 them to organize a community outreach day to share findings with neighboring
657 villages. Recognizing that the protection of trees cannot be managed effectively
658 at an individual or single-community scale, participants developed proposals for
659 collective action during this deliberative session. This initiative reflects a strong
660 community awareness and a commitment to extending the scope of conservation
661 efforts beyond their immediate environment.

662 5 Conclusion

663 This research began by identifying the aspirations of local populations, from
664 which we selected those we could feasibly address. Among these aspirations,
665 the desire for a restored environment was paramount, manifesting in our efforts
666 to increase tree populations, particularly of *Faidherbia albida*.

667 Building on this aspiration, we collaborated with local communities through
668 multiple workshops to develop an agent-based model. This model serves not
669 just as a scientific tool but as a reflection of the community’s perceived critical

relationships and strategies necessary to achieve their environmental goals. This process melds scientific experimentation with co-construction and exploratory companion modeling, ensuring that the model's outcomes are deeply rooted in both empirical research and community insights.

The results of the model should be viewed within the trajectory of the community group, indicating that they encapsulate the relationships the group deemed essential for realizing their aspirations. These results highlight collective opportunities for improving tree counts in the area but also expose contradictions, such as the competing need for firewood for cooking.

This conflict suggests that in addition to protecting young saplings, it is crucial to promote alternatives to firewood, such as the use of improved stoves or *Typha* charcoal. Protecting and increasing tree numbers in the area primarily requires supporting farmers to identify and preserve young saplings in the fields until they reach maturity.

Although the practice of marking young tree saplings for protection exists, it is not sufficiently adopted. The use of simulation to orchestrate the system of interrelationships that the actors co-constructed has been instrumental in raising awareness about the importance of collective action. This awareness has led to the organization of deliberation days on the subject with neighboring villages.

Engaging stakeholders in model exploration is an extremely powerful activity when aiming to encourage them to consider alternative futures. This participatory approach not only fosters a deeper understanding of the ecological and social dynamics at play but also empowers communities to actively participate in shaping their environmental futures.

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Author Contributions

Describe contributions of each author to the paper, using the first initial and full last name.

“L. Broutin conceived the model and realize interviews.”

“E. Delay and L. Broutin animate multi-actor focus groups.”

“E. Delay assisted L. Broutin in the development of the model and conducte the HPC exploration.”

“E. Delay realize the first draft of this manuscript.”

“All authors contributed equally to 2nd version of the manuscript.”

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717 Conflicts of Interest

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