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.

1 Introduction

Il est treize heures, la brousse d'avril est vide et silencieuse. Aucun animal en vue, aucun Homme à l'horizon, presque aucun signe de vie. Difficile d'imaginer que ces espaces sableux verront se précipiter laboureurs et planteurs d'ici peu. Les arbres eux sont là, seules petites touches vertes dans ce paysage séché. Leur ombrage est précieux mais il faut affronter le soleil pendant de longues minutes pour s'y réfugier. Ils demeurent loin les uns des autres, de façon étonnamment régulière. Plus saisissant encore : leur taille. Ce n'est pas qu'ils soient bien grands, mais tous semblables. Ils ont surement tous le même âge ! Et si c'est le cas, ils finiront tous par mourir en même temps.

La région sahélienne a été le témoin d'une série de sécheresses dévastatrices s'étalant des années 1960 aux années 1990, ayant provoqué une dégradation substantielle de ses écosystèmes, en particulier par la réduction significative de leur couvert arboré Mbow, Brandt, Ouedraogo, De Leeuw, and Marshall 2015. Cette perte de couvert arboré a eu des conséquences néfastes, se traduisant par une diminution des services écosystémiques essentiels fournis à la population et à la biodiversité. Cependant, l'ampleur de cette perte de SE est d'autant plus préoccupante que la population de la région sahélienne ne cesse de croître rapidement Cesaro, Mbaye, B Ba, et al. 2023. Dans un contexte de pénurie, l'utilisation intensive des ressources naturelles par l'agriculture et l'élevage aggrave la dégradation des terres et de la fertilité des sols Tappan, Cotillon, Hermann, Cushing, and Hutchinson 2016.

En 2018, un constat alarmant mettait en lumière le fait que près de 40% de la population mondiale était exposée aux conséquences de la dégradation des sols (Monique Barbut, Secrétaire exécutive de la Convention des Nations Unies sur la lutte contre la désertification). Dans ce contexte, les enjeux liés à la conservation et à la restauration de la fertilité des sols demeurent cruciaux. C'est dans ce contexte qu'a émergé l'initiative "4 pour 1000" (4p1000) en 2015, une proposition visant à accroître la séquestration du carbone dans les sols agricoles, présentée comme une solution pour améliorer la fertilité des sols et contribuer à l'atténuation du changement climatique Kon Kam King, Granjou, Fournil, and Cecillon 2018.

Ester Boserup Boserup and Chambers 1965 a avancé l'idée que la baisse de la fertilité des sols pousse les agriculteurs à intensifier leurs pratiques. Les travaux antérieurs cherchant à établir des liens entre phénomènes sociaux et pratiques agricoles se sont souvent centrés sur l'intensification. Toutefois, dans le cadre du projet de recherche et développement DSCATT (Dynamique de la Séquestration du Carbone dans les sols des systèmes agricoles Tropicaux et Tempérés), qui s'inscrit dans l'initiative 4p1000, notre objectif était de comprendre les relations qu'entretiennent les populations locales du bassin arachidier sénégalais avec les arbres. Pour ce faire, nous avons examiné les usages des arbres et les pratiques de gestion des populations locales afin de construire un modèle de simulation co-construit: le modèle SAFIRe (Simulation of Agents for Fertility, Integrated Energy, Food security, and Reforestation). Cette approche s'inscrit dans un cadre de Modélisation d'accompagnement (ComMod) Etienne 2014; Barreteau, Antona, D'Aquino, et al. 2003 et d'Exploration d'accompagnement (ComExp) Delay, Chapron, Leclaire, and Reuillon 2020 visant à explorer collectivement les futurs possibles pour le territoire.

Dans le contexte de la gestion durable des terres, les options de restauration identifiées par les paysans sont étroitement liées à la surveillance des arbres pour réduire les risques de prédation par les populations avoisinantes. Deux pistes d'exploration ont émergé des échanges avec les communautés locales : l'influence de la surveillance déléguée aux agents des eaux et forêt, ainsi que les conditions de développement du parc arboré lorsque la surveillance reste sous la responsabilité de la population. Cette étude vise à approfondir ces aspects dans le but de contribuer à une meilleure compréhension des pratiques de gestion durable des ressources naturelles et de la biodiversité dans un contexte sahélien en mutation.

nd The cases also demonstrate that conservation agendas tend to promote preservation of nature without people, particularly without subsistence-oriented populations, despite the claim that they are sensitive to community livelihood needs.

Or c'est bien comme ça que les population le vivent, exclue des ressource naturelle par les agens des eaux et forets. (C.f. selfa 2008)

This "reimagined" localized approach est appeller de ses voeux par Jansujwicz (2021), avec ACARDI et ComMod on coche toutes les cases

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, Niang, Touré, and Goffner 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, M Ba, Delay, and Fallot

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 Diohine, 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 aspects and modeling tools for a holistic understanding.

2.1 Modelling for Empowerment - An Anthropological Approach to Participatory Model Co-construction

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

Through these interviews, focus groupes and participant observation, a process of developing conceptual models was initiated, gradually evolving into the creation of an agent-based computational model. The co-construction of these models was a collaborative and iterative approach, actively involving the stakeholders of the Diohine Living Lab. Local actors played a key role in discussing, evaluating, and validating each aspect of the model, thereby ensuring it accurately reflected their realities and expectations.

Following a thorough validation of the model with local stakeholders, described as expert validation Bommel 2009, we began exploring the model using the OpenMole platform Reuillon, Leclaire, and Rey-Coyrehourcq 2013. This exploration phase allowed us to simulate various scenarios and gather significant results, which were then presented to the Living Lab participants for feedback and further discussion. To facilitate this crucial step, we developed an interactive interface designed to simplify the manipulation and validation of large amounts of data by the stakeholders, ensuring a smooth and collaborative experience.

2.2 ODD

In this section, we will describe the SAFIRe model (Simulation of Agents for Fertility, Integrated Energy, Food security, and Reforestation) using the ODD (Overview, Design concepts, and Details) framework Grimm, Berger, Bastiansen, et al. 2006; Grimm, Berger, DeAngelis, Polhill, Giske, and S Railsback 2010; Grimm, SF Railsback, Vincenot, et al. 2020.

2.2.1 Overview

Purpose

The peanut basin is facing a loss of soil fertility. Chemical amendments are either unavailable in the area or economically inaccessible for farmers. Therefore, soil fertility depends on two aspects: the presence of livestock in the territory to maintain year-round manure, and the Faedherbia albida trees which play a fundamental role in crop cycles. Indeed, these trees have the unique characteristic of shedding their leaves during the growing season and fixing nitrogen 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 olso 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.

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

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

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

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

Process overview and scheduling

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

- Harvest and Crop Management
  - Harvest and stockpiling: Farmers harvest crops and store them in their stockpiles.
  - Effect of machinery on unprotected saplings: Machinery used in the fields may damage or destroy unprotected saplings.

  - Crop rotation: Farmers rotate crops between different fields to maintain soil fertility and reduce pest buildup.

- Tree Growth and Reproduction
  - Sprouting: New saplings sprout around mature trees, influenced by tree density and environmental conditions.
  - Sapling growth: Saplings grow over time, with growth rates dependent on available resources and environmental factors.
  - Aging and death of trees: Trees age and may eventually die due to old age, disease, or other environmental factors.

- Livestock Feeding and Forage Use of Acacias
  - Feeding livestock with straw: Shepherds feed their livestock with straw collected from the fields.
  - Tree cutting: Trees are cut down for forage or other uses by the shepherds.
  - Livestock in fallow land and cutting of saplings: Livestock graze in fallow lands, and shepherds may cut down saplings to manage the land.

- Cutting of Saplings by Woodcutters
  - Detection of saplings: Woodcutters search for and identify saplings that can be cut.
  - Cutting of saplings: Once identified, saplings are cut by the woodcutters for use as firewood or other purposes.

- Farmer Engagement
  - Participation in meetings: Farmers participate in community meetings to discuss agricultural practices and share knowledge.
  - Observing the success of neighbors: Farmers observe the practices and successes of their neighbors to learn and adapt.
  - Social interaction and motivation: Social interactions among farmers influence their motivation and engagement in community activities.
  - Protection of saplings: Farmers take actions to protect saplings from damage by livestock or machinery.

- Surveillance
  - Surveillance and presence of farmers in the fields (generalized community surveillance): Farmers patrol their fields and monitor for any issues such as pests or unauthorized grazing.
  - Delegated community surveillance: Specific individuals or groups are assigned the task of community surveillance to ensure all fields are monitored effectively.

2.2.2 Design Concepts

Basic principles

In their paper Roupsard, Audebert, Ndour, et al. 2020, a link was established between the presence of *Faidherbia albida* trees and the improvement of crop yields in the 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, Vayssières, Bourgoin, and Masse 2018; M Ba, Bourgoin, Thiaw, and Soti 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, Du Toit, and Pollard 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.
- Number of Trees at Each Development Stage: This metric measures the number of trees at various stages of development, such as saplings, young trees, and mature trees. It provides insight into the growth dynamics and regeneration of the forest.
- Number of Trees Destroyed by Each Type of Agent: This indicator counts the number of trees destroyed by different agents, such as farmers, woodcutters, and livestock. It helps understand the impact of various human and animal activities on the forest.
- Volume of Wood Cut for Cooking: This metric tracks the amount of wood harvested specifically for cooking purposes. It helps assess the pressure on forest resources for domestic energy needs.
- Age of Each Tree Sapling: This indicator measures the age of each sapling in the simulation. It provides information on the regeneration rate and the survival of young trees.
- Number of Farmers Engaged in the RNA: This metric tracks the number of farmers actively participating in the National Agricultural Network (RNA). It helps evaluate the level of community involvement and engagement in agricultural and environmental initiatives.

2.2.3 Details

Initialization

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

- Generation of Parcels and Crops: The landscape is divided into parcels, each designated for specific types of crops. This step sets up the agricultural fields and assigns crop types to each parcel.
- Generation of Trees and Their Fertilizing Effects: Trees are distributed throughout the environment, considering their effects on soil fertility. Trees influence the nutrient levels of the patches they occupy, enhancing soil quality in their vicinity.
- Generation of Human Agents: Human agents, including shepherds, woodcutters, farmers, and supervisors, are created and placed in the environment. Each agent type has specific roles and behaviors that contribute to the model's dynamics.

- Generation of the Village: The village is established as a central location where human agents reside. This step involves setting up the village infrastructure and assigning homes to the agents.

Input data

We dont use input data.

Submodels

2.3 Statistical Analysis and our Companion Modeling approch

Our work is grounded in the approach of companion modeling Barreteau, Antona, D'Aquino, et al. 2003. However, we aim to address the pressing need for model exploration. This entails combining and hybridizing elements that are rarely integrated: exploring the model alongside the stakeholders. To achieve this, we employed traditional agent-based modeling tools and made a concerted effort to conduct these analyses with the farmers of the peanut basin, engaging them in discussions about the exploration results. We performed a sensitivity analysis and utilized the "pattern space exploration" method to produce results reflecting the range of possible long-term scenarios. These results were then discussed with the stakeholders to ensure a comprehensive understanding and validation.

2.3.1 Sensitivity analysis : saltelli method

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

2.3.2 Pattern Space Exploration (PSE)

The PSE Chérel, Cottineau, and Reuillon 2015 method, based on genetic algorythme, is specifically designed to comprehensively cover the output space, resulting in its maximum score in output exploration – e.g. "explore the output's diversity of a model"[1]. By exploring the output space (c.f. fig. 1), the

[1] `https://openmole.org/PSE.html`, consulté le 5 juin 2023

PSE method uncovers new patterns, providing insights into the model's sensitivity by examining the corresponding input values. Unlike calibration-based methods, PSE's effectiveness is influenced by the dimensionality of the output space, as it keeps a record of all the covered locations during exploration.

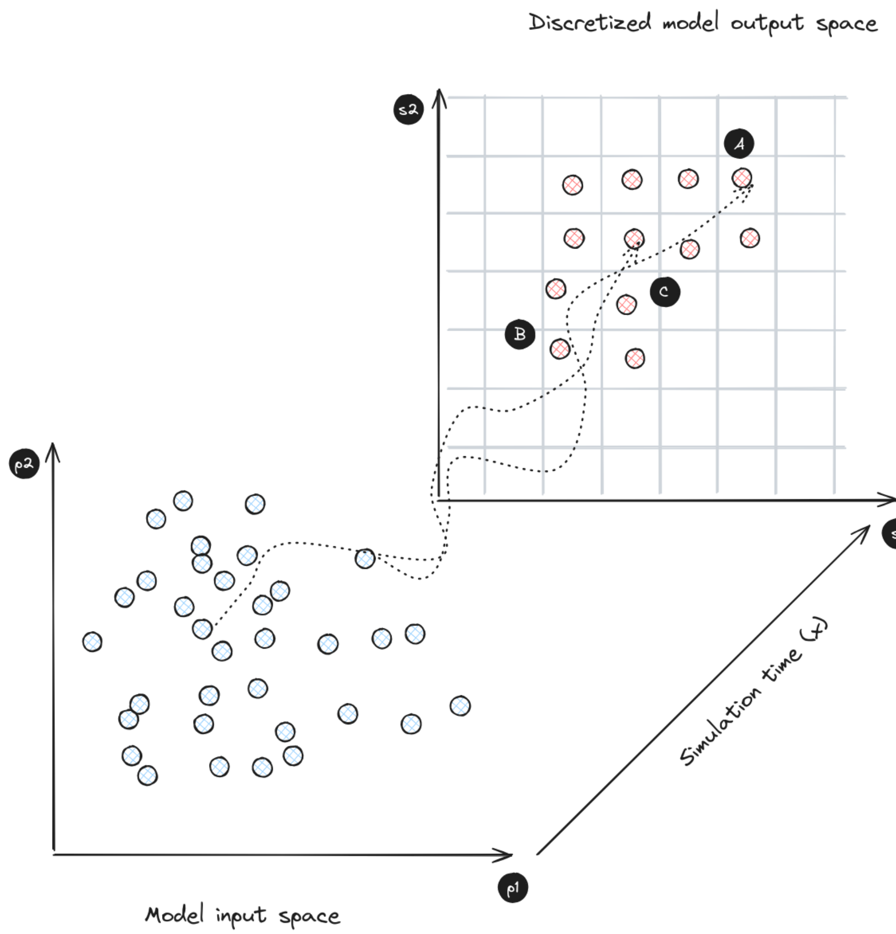


Figure 1: description of how the "pattern space exploration" genetic algorithm works. We see "p1" and "p2" as input parameters, and "s1" and "s2" as output parameters. The algorithm seeks to reach every cell in the grid of "s1" and "s2" to discover the model's output result domains. A and B and C are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

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

The algorithm's ability to explore a diversity of output forms is extraordinarily powerful in the context of companion modeling. Indeed, participants in co-construction sessions gradually became accustomed to the practice of modeling Etienne 2014. They developed the ability to interrelate various elements of the system. However, the strength of agent-based modeling lies in the fact that they cannot anticipate emergent phenomena. Once the model has gained sufficient confidence, questioning the group about marginal aspects or unconsidered input parameter sets in the model proves to be extremely fruitful from the perspectives of emancipation and anticipating unforeseeable situations.

2.3.3 Engaging Stakeholders in Result and Thresholds Discussions

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

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

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

3 Results

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

Following this, we conducted a Pattern Space Exploration (PSE) to identify the simulations that, in the context of community surveillance, increase the number of trees. This is a nonlinear process with an increase in fertility 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).

he 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 fréquance 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

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.

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

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.

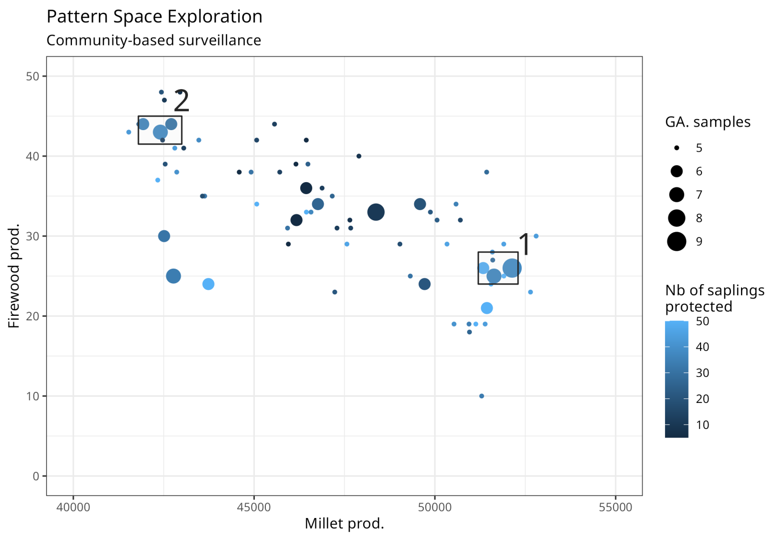
If we then look at the influence of the type of tree surveillance. By comparing the two scenarios, we can see that simulations reaching the numbered spaces 1 and 2 on Figure 2a, representing community surveillance, are less present on Figure 2b, which represents the delegated surveillance scenario. Conversely, 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.

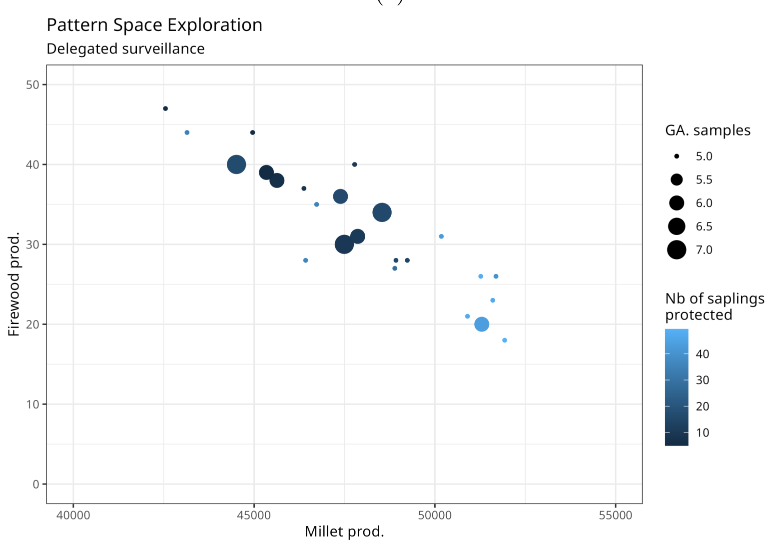
In both situations, reducing the harvesting of firewood leads to a higher number of seedlings. In both cases, these situations are reached by simulations where RNA and the diffusion of practices are present in the form of awareness meetings.

3.3 Unexpected Yet Attainable: Surprising Results with Minimal Calculations

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



(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.

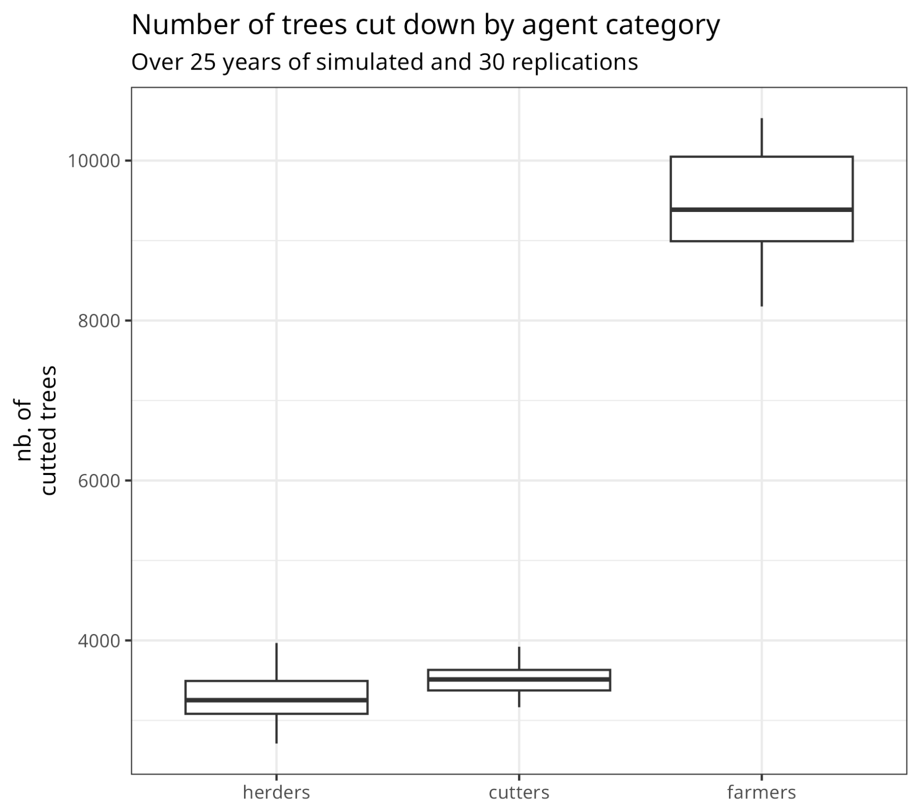


Figure 3: Boxplot showing the total number of trees cut down at the end of the simulation by resource user category. It is evident that farmers are responsible for the highest number of trees removed from the system across all categories. These results are based on 30 replications of the same parameter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

the management of tree resources within the community.

4 Discussion

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

He et al 2020 les bénéfice d'impliquer les popoulation locale dans la gestion de la nature - c'est vrai en europe Obradović et al 2022 - it is necessary for conservation to consider the use of natural resources from a systematic view by linking the natural resource use of the local community to conservation (selfa 2008) and The cases also demonstrate that conservation agendas tend to promote preservation of nature without people, particularly without subsistence-oriented populations, despite the claim that they are sensitive to community livelihood needs.

Or c'est bien comme ça que les population le vivent, exclue des ressource naturelle par les agens des eaux et forets.

4.1 Discussion des résultats du modèle

- Analyse de Sensibilité : L'analyse de sensibilité globale montre que, dans un scénario de surveillance communautaire, la probabilité de discuter de l'importance des arbres joue un rôle crucial tant pour la production de mil (0.72) que pour le nombre total d'arbres (0.59). Cela indique que les discussions et la sensibilisation au sein de la communauté sont essentielles pour la gestion des ressources arborées.

- Influence de la Surveillance Déléguée : Dans un scénario où la surveillance est effectuée par un agent des eaux et forêts, la dynamique change. Le temps passé au champ et la probabilité de discuter de la préservation des arbres restent des paramètres influents, mais d'autres facteurs, comme le nombre de surveillants, prennent également de l'importance. La fréquence des réunions et la probabilité de dénoncer un coupeur ont une influence réduite, suggérant que la surveillance déléguée modifie les dynamiques de gestion communautaire.

- Exploration de l'Espace de Modèles (PSE) : L'exploration PSE révèle une relation négative entre la production de mil et la production de bois de chauffage. Les simulations atteignant les extrêmes indiquent que la réduction de la récolte de bois de chauffage favorise un plus grand nombre de jeunes plants protégés. Les résultats montrent également que la sensibilisation et la diffusion des pratiques par le biais de réunions de sensibilisation sont présentes dans les simulations les plus efficaces.

4.2 La porté tranformatice de la modélisation d'accompagnement

- mise en lumière des solutions réel et de leurs implications (surveillance communautaire améliore l'un ou l'autre des objectifs)

- Identification de Problèmes Cachés : En intégrant des indicateurs de base dans le modèle, nous avons mis en lumière un problème fondamental que les participants du Living Lab n'avaient jamais considéré comme majeur : l'impact significatif des agriculteurs sur la destruction des arbres. Cette destruction passe souvent inaperçue car elle se manifeste par le désherbage des jeunes pousses, une action que les agriculteurs ne perçoivent pas toujours comme une menace pour les ressources arborées.

- Clarification des Techniques Agricoles : La discussion de ces résultats pendant l'atelier a permis de clarifier les techniques agricoles et de s'assurer que leur traduction dans le modèle était fidèle à la réalité. Cela a renforcé la pertinence et la précision du modèle, tout en améliorant la compréhension des participants sur les dynamiques en jeu.

4.3 perspectives

- on peut également se posé la question de la mise en pépinière d'arbre pour essayer d'atteindre la fertilité
- il faudrait trouver des mettrique qui permette d'identifier les grand changement dans les dynamique du modèle (mathas et al.)

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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 intervews."

"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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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article.

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