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

E. Delay[1,2,6*†], L. Broutin[1,2,4†], A. Fallot[1,2], A. Perrotton[3], A. Gonin[4], and D. Masse[5]

[1]CIRAD, UMR SENS, F-34398 Montpellier, France.
[2]SENS, CIRAD, IRD, Université de Paul Valéry Montpellier 3, Montpellier, France.
[3]Forêts et Sociétés, Univ Montpellier, CIRAD, Montpellier, France.
[4]Université Paris Nanterre, Laboratoire LAVUE, FR.
[5]IRD, Eco&Sols, Abidjan, Côte d'Ivoire.
[6]UMI UMMSCO, Université Cheick Anta Diop, Dakar, Sénégal.
[*]Address correspondence to: etienne.delay@cirad.fr
[†]These authors contributed equally to this work.

**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 [1]. 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 [2]. 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 [3].

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 [4].

Ester Boserup (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) [5, 6] et d'Exploration d'accompagnement (ComExp) [7] 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.

# 2 Materials and Methods

# 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 [8]. 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 [9]. 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 [10], we began exploring the model using the OpenMole platform [11]. 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 [12–14].

### 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**

**Objectives**

**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**

**Sensing**

**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**

### 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 [6]. 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)[15], 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 [16] 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 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.

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 [5]. 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

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

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 [17]. 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

L'algorime de PSE demande à discretiser l'espace des sorties de modèles. Son objectif est alors de criblé la diversité de cet espace des sorties. Nous avons paramétré l'objectif pour qu'il ne conserve comme pertiant que les résultat qui sont atteinte dans 95% des cas de la simulation. Les paramètre d'entrer – tabe 3 – sont laissé libre pour permettre la recherche.

Sur la figure 2 on a filtré les résultats qui ont été atteint plus de 4 fois par le modèle pour se concentré sur les situatiuon les plus probable. On constate qu'il y a une relation négative entre la production de mil et la production de bois de chauffe.

Viabilité du système

## 3.3 Unexpected Yet Attainable: Surprising Results with Minimal Calculations

Dans le cadre de la co-construction du modèle de simulation, en ayant intégré quelques indicateurs de base, nous avons mis en lumière un problème fondamental qui n'avait jusqu'alors jamais été évoqué

| 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

par les participants du Living-Lab. En suivant attentivement le suivi du nombre d'arbres coupés, que ce soit par les bergers pour le bétail, par les femmes pour le bois de chauffage, ou encore par les agriculteurs lors de leurs activités agricoles, une tendance surprenante est apparue, comme illustré dans la Figure XX. Il ressort de cette analyse que ce sont les agriculteurs eux-mêmes qui contribuent de manière significative à la destruction d'arbres, bien que leur action soit, dans une certaine mesure, silencieuse. Plus précisément, cette destruction passe souvent inaperçue, car elle se manifeste par le désherbage de très jeunes pousses, effectué par les agriculteurs sans qu'ils en aient pleinement conscience. Cette observation remet en question certaines perceptions antérieures et soulève des questions essentielles quant à la gestion des ressources arborées au sein de la communauté.

# 4 Discussion

Include a Discussion that summarizes (but does not merely repeat) your conclusions and elaborates on their implications. There should be a paragraph outlining the limitations of your results and interpretation, as well as a discussion of the steps that need to be taken for the findings to be applied. Please avoid claims of priority.

# Acknowledgments

## General

We warmly thank the residents of Diohine for their hospitality, with special thanks to: Aissatou Faye, Robert Diatte, Pierre Faye, Paul Sene, Ameth Paul Thiaw, Assane Diouf, Guedj Diouf, Nicolas Diouf, Ablaye Faye, Idrissa Faye, Maire-Hélène Ndjira Diouf, Seynabou Gakou, Joseph Sene, Ndeye Thiamal.

## 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 conducte the HPC exploration."

"E. Delay and L. Broutin realize the first draft of this manuscript."

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

## Funding

This work is part of the research and development project DSCATT (Dynamics of Soil Carbon Sequestration in Tropical and Temperate Agricultural Systems, https://dscatt.net/FR/index.html) co-funded by Agropolis Fondation [reference ID 1802-001] through the "Investissements d'avenir" program Labex Agro [ANR-10-LABX-0001-01] within the framework of I-SITE MUSE [ANR-16-IDEX-0006] and supported by the TOTAL Energies Foundation.

## Conflicts of Interest

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

# References


1. Mbow C, Brandt M, Ouedraogo I, De Leeuw J, and Marshall M. What Four Decades of Earth Observation Tell Us about Land Degradation in the Sahel? Remote Sensing 2015;7:4048–67.
2. Cesaro JD, Mbaye T, Ba B, et al. Reforestation and sylvopastoral systems in Sahelian drylands: evaluating return on investment from provisioning ecosystem services, Senegal. Frontiers in Environmental Science 2023;11.
3. Tappan GG, Cotillon S, Herrmann S, Cushing WM, and Hutchinson JA. Landscapes of West Africa - A Window on a Changing World. 2016. Medium: pdf Publisher: U.S. Geological Survey.
4. Kon Kam King J, Granjou C, Fournil J, and Cecillon L. Soil sciences and the French 4 per 1000 Initiative—The promises of underground carbon. Energy Research & Social Science. Special Issue on the Problems of Methods in Climate and Energy Research 2018;45:144–52.
5. Etienne M, ed. Companion Modelling: A Participatory Approach to Support Sustainable Development. Springer Netherlands, 2014. DOI: 10.1007/978-94-017-8557-0. URL: https://www.springer.com/fr/book/9789401785563 (visited on 11/07/2020).
6. Barreteau O, Antona M, D'Aquino P, et al. Our Companion Modelling Approach. Journal of Artificial Societies and Social Simulation 2003;6.
7. Delay E, Chapron P, Leclaire M, and Reuillon R. ComExp : une manière d'introduire l'exploration avec les acteurs. In: Le Cauvel, France: ComMod, 2020. URL: https://agritrop.cirad.fr/596985/ (visited on 05/02/2021).
8. Delay E, Ka A, Niang K, Touré I, and Goffner D. Coming back to a Commons approach to construct the Great Green Wall in Senegal. Land Use Policy 2022;115:106000.
9. Perrotton A, Ba M, Delay E, and Fallot A. Définition collective d'un futur désirable pour la zone de Diohine, Sénégal : Implementation de la méthode ACARDI à Diohine au Sénégal. In: Section: CIRAD-ES-UPR Forêts et sociétés (FRA); Université Gaston Berger (SEN); CIRAD-ES-UMR SENS (SEN); CIRAD-ES-UMR SENS (FRA) 3. public: ISRA, 2021:1 p. (Visited on 12/07/2021).
10. Bommel P. Définition d'un cadre méthodologique pour la conception de modèles multi-agents adaptée à la gestion des ressources renouvelables. These de doctorat. Montpellier 2, 2009. URL: https://www.theses.fr/2009MON20043 (visited on 10/25/2023).
11. Reuillon R, Leclaire M, and Rey-Coyrehourcq S. OpenMOLE, a workflow engine specifically tailored for the distributed exploration of simulation models. Future Generation Computer Systems 2013;29:1981–90.
12. Grimm V, Berger U, Bastiansen F, et al. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 2006;198:115–26.

13. Grimm V, Berger U, DeAngelis D, Polhill J, Giske J, and Railsback S. The ODD protocol:A review and first update. Ecological Modelling 2010;221:2760–8.

14. Grimm V, Railsback SF, Vincenot CE, et al. The ODD Protocol for Describing Agent-Based and Other Simulation Models: A Second Update to Improve Clarity, Replication, and Structural Realism. Journal of Artificial Societies and Social Simulation 2020;23:7.

15. Saltelli A, ed. Global sensitivity analysis: the primer. OCLC: ocn180852094. Chichester, England ; Hoboken, NJ: John Wiley, 2008.

16. Chérel G, Cottineau C, and Reuillon R. Beyond Corroboration: Strengthening Model Validation by Looking for Unexpected Patterns. PLOS ONE 2015;10. Publisher: Public Library of Science:e0138212.

17. Banos A. La simulation à base d'agents en sciences sociales : une béquille pour l'esprit humain ? Nouvelles perspectives en sciences sociales : Revue internationale de systémique complexe et d'études relationnelles 2010;5:91–100.

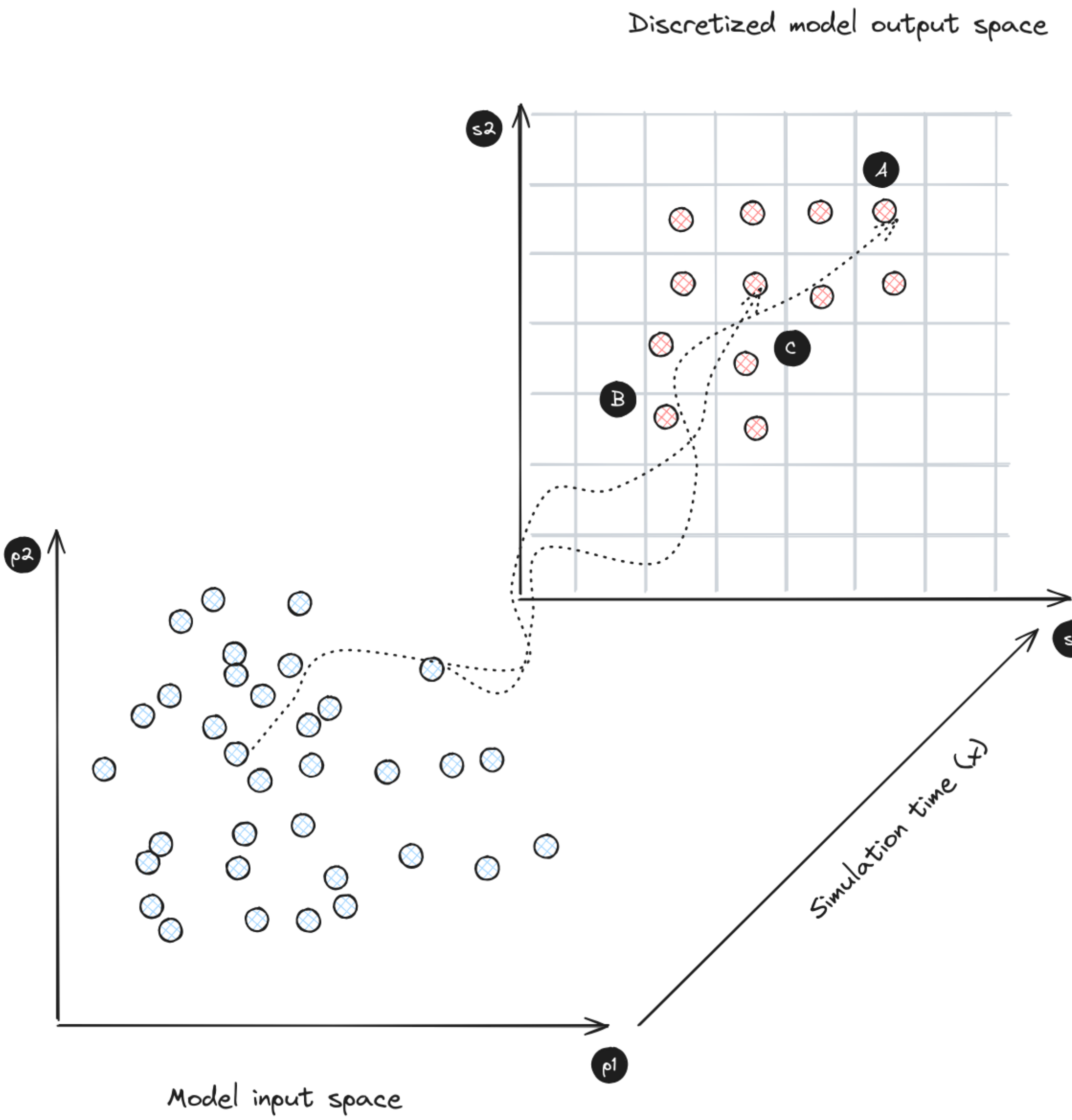
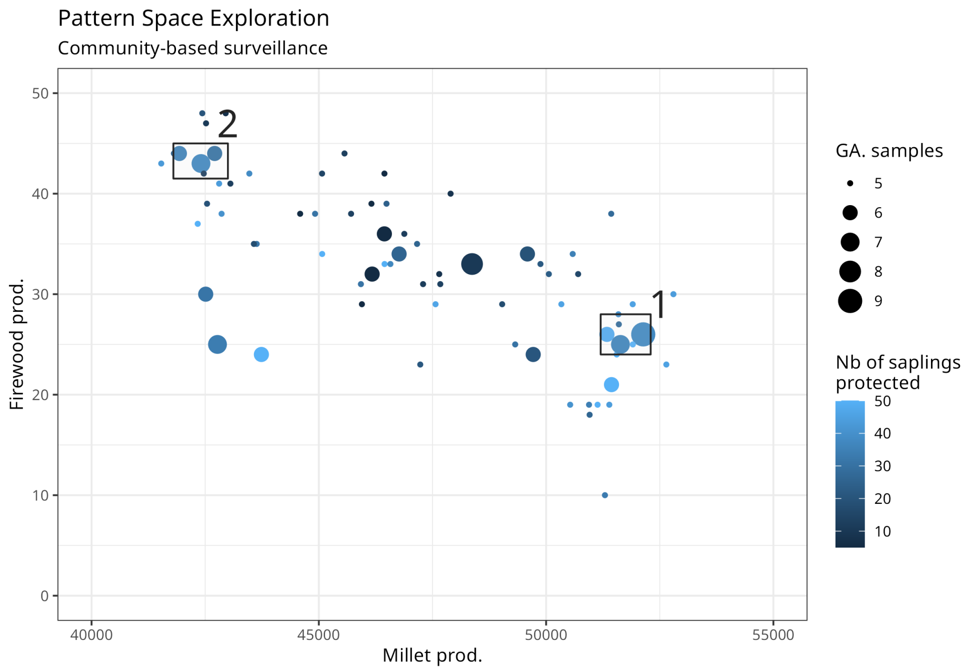
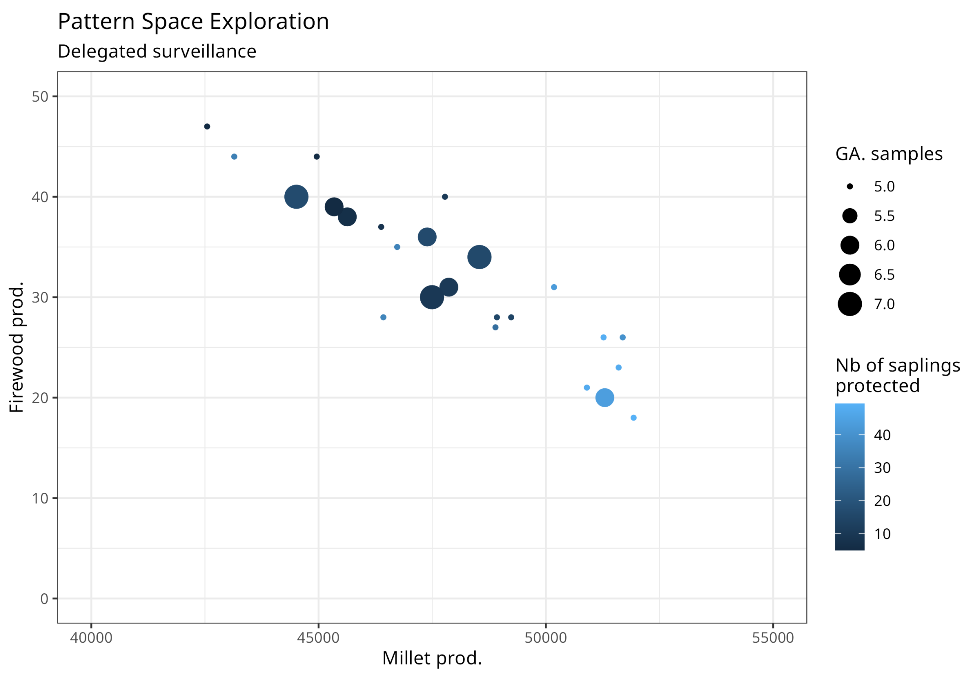



Figure 1: description of how the “pattern space exploration” genetic algorithm works. We see ”p1” and ”p2” as input parameters, and ”s1” and ”s2” as output parameters. The algorithm seeks to reach every cell in the grid of ”s1” and ”s2” to discover the model’s output result domains. A and B and C are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




(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.