Ecological scales and use rights: the use of multi-agent systems

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Abstract

The interactions between natural forest dynamics and social dynamics have to be taken into account when managing the use of forest resources. We have developed simulation models to improve our understanding of this complex system of interactions. Models of multiagent systems are effective tools for studying the dynamics of complex adaptive systems. We have developed several simulation models in order to study the use of forest resources.

This paper present a model designed to understand the interaction between fuelwood consumption and landscape dynamics. The hypothesis put forward suggests that fuelwood consumption can explain the landscape changes that occur in the Kayanza region of Burundi. The second hypothesis is that a sustainable use of resource must keep steady the fuelwood consumption level per capita over the time.

A preliminary map was outlined; agents use fuelwood, have access to different parts of space and have the capacity to exchange use rights. The population increases and agent migration—from overpopulated areas to unoccupied plots—is simulated. The impact of changing rules on foraging, exchange and access is then observed on a landscape level.

The model describes here the behaviour of different agents (farmers, local consumers, exporters and traders). The impact of their behaviour and interactions are evaluated on different scales, ranging from the individual plot to the forest and the landscape.

Models and multiagent systems can effectively represent processes that occur at levels of varying complexity and simulate their interactions so that landscape dynamics can be understood from the bottom up.

KeyWords : Multi-agent systems, fuelwood, access rights, social exchanges, spatial scales

1. Introduction

At the interface between natural and social dynamics, environmental research is tackling development problems by examining questions that relate to resources and externalities. These include the management of renewable resources, externalities of production (pollution, effluent, etc.) and areas with multiple uses. Natural dynamics are made up of numerous interweaving processes involving different resources on different spatial and temporal scales. Social processes involve different stakeholders at various levels of organization, ranging from individuals or communities that use resources and spaces to large development institutions. The issues focus on the regulation of resource use—that is adapted to natural dynamics—through the application of economic, legal or institutional management tools. In all cases, the issues relate to problems of collective management where ecological processes have to be reconciled with social processes for resource use.

The essence of ecology is to examine ways of approaching the study of complex systems. A complex entity (Fogelman Soulié, 1991; Gell-Mann, 1994) is made up of different elements that interact and combine in such a way that is not immediately obvious: the complexity of a system is in the eye of the beholder. The idea that perception is inextricably linked to the notion of complexity is not impartial: it reflects the importance of the levels chosen for observing a given system. In ecology, there is no natural scale for observing all types of phenomena. Conventionally, the hierarchy of scales (Allen and Starr, 1982) refers to levels of organization: cell, organism, population, community, ecosystem, landscape, biome and biosphere. One of the major challenges facing ecology is being able to take into account a multiplicity of scales of study in order to integrate—during a phase called "transfer of scale"—each of the phenomenon studied at their specific level.

Indeed, one of the problems facing modelling is how to represent dynamics on different scales.

Natural resource and environmental economics propose a range of theories and concepts with tools for monitoring, analysis, evaluation and regulation (Dales, 1968; Arrow and Fisher, 1974; Bromley, 1991). In particular, economics provides a model for the use of renewable resources that aims to control sustainability of use by applying regulatory or incentive mechanisms, such as taxes, quotas, licences, grants, standards, permits, definition and exchange of property rights. It is also important to understand decision-making processes which are defined as the interactions between stakeholders with different representations and power. The problem is understanding how resource use is regulated. This can be achieved by modelling the representations and exchanges (of goods, services, currency and information) and the global constraints expressed by the use of regulatory or incentive mechanisms.

Therefore, the interaction between ecological and socioeconomic dynamics can be understood by modelling interactions on different scales. We have chosen multiagent systems (MAS) for this purpose. In this article, we start by introducing the MAS that we used. We then go on to describe an example of a model that takes into account ecological dynamics on several levels as well as the exchanges between agents with different representations.

2. Materials and Methods: multiagent systems

2.1. Multiagent systems

The aim of multiagent systems (Ferber, 1999) is to understand how independent processes in direct competition are coordinated. An agent is thus a computerized process, something that comes between a computer programme and a robot. An agent can be described as autonomous because it has the capacity to adapt when its environment changes. A multiagent system is made up of a set of computer processes that occur at the same time, ie several agents that exist at the same time, share common resources and communicate with each other. The key issue in the theory of multiagent universes is formalizing the necessary coordination between agents. The theory of agents is therefore a theory of:

1. Decision-making: what decision-making mechanisms are available to the agent? What are the links between their perceptions, representations and actions ?
2. Control: what are the hierarchic relationships between agents? How are they synchronized?
3. Communication: what kinds of message do they send each other? What syntax do these messages obey?

for which elaborate formulas are put forward.

Multiagent systems can be applied to artificial intelligence. They simplify problem-solving by: dividing the necessary knowledge into subunits, by associating an intelligent independent agent to each subunit, and by coordinating the agents' activity. Thus, we refer to distributed artificial intelligence. This theory can be applied to monitoring an industrial process, for example, where it adopts the sensible solution which consists of coordinating several specialized monitors rather than a single omniscient one. Fundamental research is being conducted on the problems associated with the representation of agents' decisions and protocols for communication. The main applications for MAS are in telecommunications, internet and physical agents, such as robots (Weiss, 1999). There is a group of scientists that specializes in the simulations of agents' societies in ecology and social sciences.

Research has been conducted in parallel by computer scientists, ecologists and social scientists on the principle of modelling distributed systems. Here, we discuss a few references and some of the issues involved.

2.2 MAS and Ecology

In ecology, the distributed approaches, known as individual-based models (IBM) were developed at the end of the 1980s. The article written by Huston (Huston, DeAngelis *et al.*, 1988) is the most frequently quoted. The authors argue that there are two reasons for developing this approach: first, the need to take into account the individual because of their genetic uniqueness and, secondly, the fact that each individual is situated and their interactions are local. The argument clearly had an impact because numerous publications refer to this approach. Shortly after this publication, Hogeweg and Hesper (Hogeweg and Hesper, 1990) published a similar article on "individual-oriented modelling". This had more influence on scientists working in the field of artificial life. Then, in 1990, there was a congress in Knoxville on "Individual-based models and approaches in ecology". The congress' proceedings were published and have since been the main reference text on the subject (DeAngelis and Gross, 1992).

Above all, truly individual-based models, or so-called i-state configuration models (Maley and Caswell, 1993), have been used for the object-oriented approach, for example, the work by Silvert (Silvert, 1993), Derry (Derry, 1998) and Roese (Roese, 1991). There are several models of forests (Deutschman, 1997; Liu, 1998). The most striking application is undoubtedly the Across Trophic Level System Simulation (ATLSS) model which attempts to simulate the ecological function of the Everglades in Florida (Abott, Berry *et al*. 1995). This model represents abiotic factors—such as hydrology, fire and hurricanes—and different trophic levels simultaneously. Within the models, which can be mathematical compartmental models, different animal populations are simulated (deer, fishs) with the help of individual-based models.

2.3. MAS and social sciences

MAS are developing rapidly in the field of social sciences. Society simulation is the subject of numerous conferences, for example, Multi Agent systems and Agent Based Simulation (MABS) (Sichman, 1998) among others (Conte, 1997). Research on the subject is published in the electronic journal Jass (Journal of artificial societies and simulation). In addition, a group called Agent-based Computational Economics (ACE) (Tefstation, 1997) has been set up.

In social sciences, the application of the theory of multiagent universes to simulate social phenomena is generally associated with the methodological individualism (Havelange, 1994; Lenay, 1994) in which the singular individual is considered as the elementary unit or the atom of society (Weber, 1971). The overlap is, in fact, in the bottom-up approach which characterizes MAS. However, the assimilation between individuals from a society and agents from a multiagent universe can be misleading: it is quite possible for social groups and institutions to be considered as agents with their own standards and rules for functioning (Livet, 1987). The agents are directed by constraints or rules that are expressed on a group level, ie they are no more than entities that act and are placed in a dynamic environment.

This straightforward comment—which is natural when MAS are used for modelling—shows how the simple duality that exists between individualism and holism can be called into question, which is a major preoccupation for researchers working on renewable resource management and MAS:

(i) individuals, products of history are driven by collective values and rules,

(ii) collective values and rules evolve because of the interaction between individuals and between groups,

(iii) the individuals are neither similar nor equal but have their own specific roles and social status.

How do individuals make up a group? How is an institution created? The individual cannot be considered as an autonomous entity that is independent of its social environment. How are individuals constrained by collective structures that they themselves have set up and how do they make these structures evolve (Gilbert, 1995)? What degrees of freedom are given to the definition of individual practices? Here are just some of the questions that can be explored using MAS and which can be expressed as follows: "how are collective structures set up and how do they function when they are based on agents with different capacities of representation, that exchange information, goods or services, etc., draw up contracts and are thrust into a dynamic environment which responds to their actions?"

2.4. MAS and interactions between societies and resources

The problem with modelling common resource management is the simulation of the interaction between groups of agents and dynamics of resources. Empirically, there are several ways of modelling these interactions.

The first method involves simulating how social networks are managed. Here, we consider that the relationships between people and resources should, in fact, be formulated as the relationships between people that concern resources. Agents that exchange messages within networks or so-called contact networks can be simulated with MAS. In this way, exchanges of information and services, contracts and agreements between agents can be simulated. For example, in the case of irrigated systems, farmer agents can send each other messages so that they know what the water levels are in different plots, they can ask for or exchange services or addresses. In this way, it has been shown (Barreteau and Bousquet, in press) that the evolution of a system can be very sensitive to the structure and dynamics of social networks.

In the second method, emphasis is put on the cognitive processes or representations that determine how agents and resources interact. Each agent develops and then acts on its own representation of a resource. In so doing, the agent transforms the resource for the other agents. This model represents interactions that are close to what economists call externalities. We study the problem of managing common renewable resources by examining the different representations of actions that affect the resources in question. The resulting resource use may or may not be satisfactory for the agents. This can be described as coordination through the environment.

This method of classification provides a framework. Applied models can take into account both the agents' interactions and systems of exchanges through the environment.

2.5. Cormas: multiagent simulation software

For several years now, multiagent simulation software has been available. User groups (including ecologists and sociologists) are organized around generic tools that facilitate the construction of models and offer facilities ("virtual laboratories") for monitoring and analysing simulation trials. The example of Swarm[1]—which uses the object-oriented language Objective-C for writing code and Tcl/Tk for developing interfaces—clearly reflects the current trend. Since the launch of the project at the Santa Fe Institute in 1994, groups using Swarm have joined forces to try and resolve common problems. As a result, new software based on Swarm, with specific applications for different disciplinary fields (ecology, for example), has been developed.

Our team is particularly interested in models for resource management. Hence, the multiagent simulation software that we have developed is based on the concept that space holds resources. The software Cormas is an environment for constructing multiagent models based on the software VisualWorks which, in turn, is a programming environment within Smalltalk. Cincom, the American company that markets VisualWorks distributes the software freely (for educational and research purposes). Cormas is also available to the scientific community[2] in the form of a set of programmes that are downloaded in VisualWorks.

Cormas is made up of different sets of programmes. The first is for modelling agents and interactions; these interactions are mediated either through a simulation space in the form of a set of cells or via messages. The second set of programmes involves the control of the dynamics of the simulation, whereas the third set of programmes is for defining the observer's different points of view.

Several types of entity can be defined using Cormas. All the entities in Cormas possess **primitives** (programmes) which allow the exchange of resources on request (be it *pro rata*, **the most sought after** or as a function of the agents' characteristics, etc.).

Here, we describe the entities used for the model presented below.

- The first is called the situated agent. A situated entity has spatial references (the cell). It is characterized by its perception range.
- The second is the cell. Space is a component that is taken into account by Cormas. Above all, it is the support for situated agents. Thus, the cell has a list of located agents that are situated on it. The cell provides primitives for access to neighbouring cells within a varied radius. The space also has its own dynamics. As with cellular robots, the cells are characterized by a state that can change dynamically depending on rules that take into account the state of neighbouring cells.
- The third is the spatial aggregate. When MAS are used to simulate spatial dynamics, the question is how can the spatial agents and the rules that govern their spatial interactions be simulated on different levels? We simulated spatial dynamics—with their own specific behaviour patterns—based on geographic entities (forest, town, road, etc.) at a higher level of organization than that of the cell.

3. An example of results: a model for fuelwood consumption

The model described here was developed for research concerning fuelwood consumption in the Kayanza region of Burundi. In the last century, this region has faced various events: changes in access rights and development of plantations. One has observed simultaneously increases in crops and forest area. The model has been designed to test these dynamics and events and discuss their combined effects.

3.1. The model

We developed a model with three different entities: the cell—which represents 1 ha of space—the forest, which is an aggregate entity that represents forests—and the household agent, which represents a family living on one cell. We describe the three entities and then go on to describe the control algorithm which determines how the three different entities behave. The time step chosen for the simulation is equal to 1 year. The space under study is made up of a set of 10 000 hexagonal cells which have six adjacent cells. Thus, a region of 100 km² is represented (Figure 1).

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[1] http://www.swarm.org

[2] http://www.cirad.fr/presentation/programmes/espace/cormas/

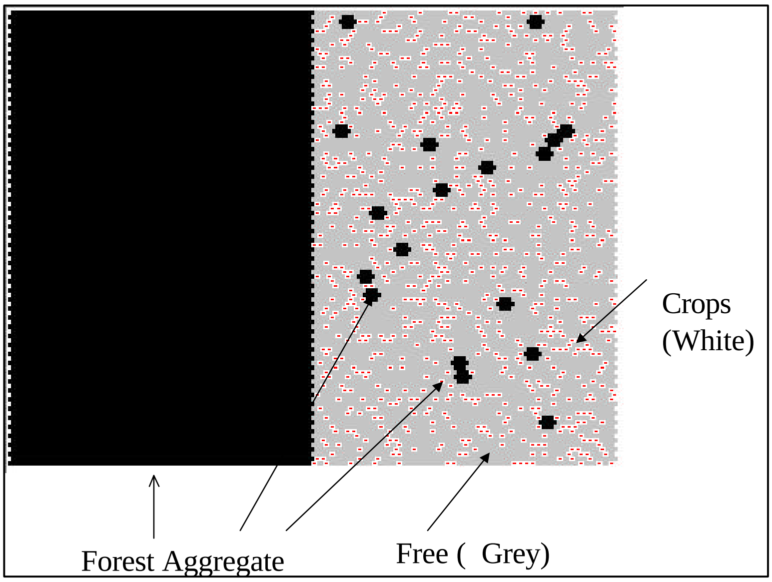

Figure 1 Initial state

3.1.1 Description and dynamics of a cell

The cell is characterized by six variables:

- state: this variable relates to one of five values (forest, degraded forest, pasture, cropland and agroforestry). The transitional function of the cell, ie the rules that determine a change of state, is outlined in Figure 2.

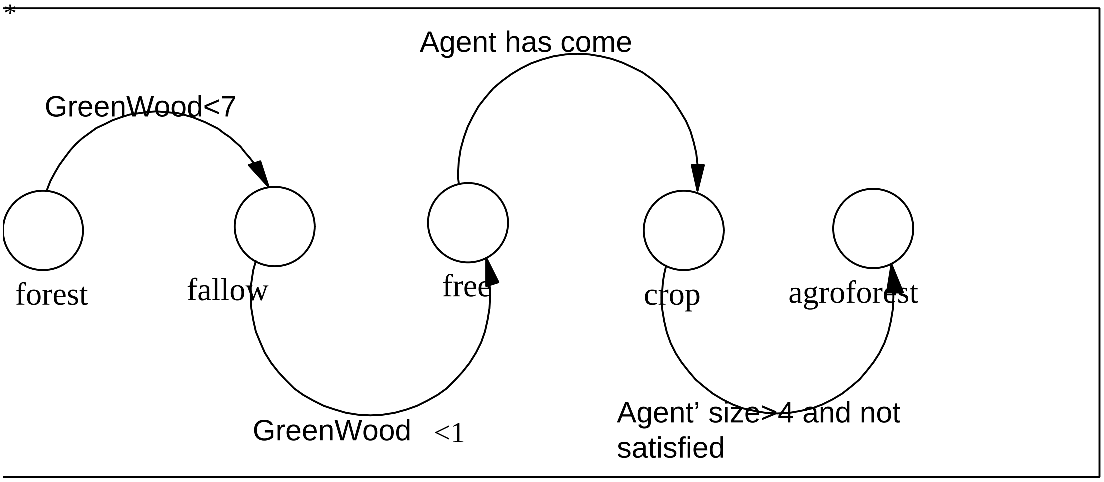

Figure 2. Transitional function. Each circle represents a potential state that a cell can adopt. The arrows represent the possible transitions and the text describes the conditions necessary for the transitions.

- Live wood: this variable represents the quantity of standing wood (measured in m³) on the cell. When the cells are initialized, the variable is set at 300 m³ if the cell is in the forest state. The dynamic of this variable is simulated according to the logistic model. When a cell is in the agroforestry state, which simulates the fact that the agent on the cell has planted trees, the initial stock of live wood is 20 m³.
- Dead wood: this variable represents the quantity of dead wood (measured in m³) on a cell. Its value corresponds to a proportion of live wood.

$$\text{Dead wood}_t = \text{live wood}_t/20$$

- Access: this variable can have either a true or a false Boolean value. Depending on its value, live wood may or may not be harvested.

- Buffer wood. This variable acts as a stock for ecological production. In addition, the cell in this model also includes programmed generic programmes on the same level as Cormas. Thus, a cell is capable of stocking all the agents' requests for live or dead wood before distributing quantities of these resources *pro rata* according to demand.

3.1.2. The forest aggregate

The aggregate forest is made up of sets of contiguous cells that are in a forest or degraded forest state. The aggregate is capable of defining its border and determining subunits of cells that are at a certain distance from a given point. Thus, an agent situated at a certain distance from the aggregate forest can ask the latter which cells it can collect wood from. In this way, the aggregate forest controls the distribution of wood and determines the order in which the cells produce wood. If the case arises in the model, the most degraded cells (with the least live wood) produce wood first. Thus, the model represents the fact that habits develop and fuelwood harvesting is concentrated in certain parts of the forest.

3.1.3 The household agent

The household agent is characterized by six variables:

- Population: Population growth is simulated at 3%. For every time step, a random distribution simulates this growth. The phenomenon of migration is also simulated. The probability of migration is 10% for a household of four people, 30% (five people), 50% (six people), 70% (seven people), 90% (eight people) and 100% for households of nine or more. There is a random draw in these distributions and the population size is eventually reduced by one unit. There are four people per household to start with.
- Wood space: this corresponds to the agent's spatial perception. It consists of all the forest cells within a perception range of 2 km (Figure 3).
- Live wood: the amount of live wood collected during one time step.
- Dead wood: the amount of dead wood collected during one time step.
- Consumption: the total amount of green and dead wood collected.
- Satisfaction: this has a true or false Boolean value depending on consumption. If consumption is greater than 90% of potential consumption ($1m^3$/person/year), satisfaction is equal to the true value otherwise it is equal to the false value.

Three supplementary programmes were written for the household agent. They relate to behaviour patterns for harvesting wood. The agent calculates how much live wood (consumption of live wood) or dead wood (consumption of dead wood) they need. It then asks the cells in its perception range (wood space) for this amount of wood. The third programme (local consumption) corresponds to the amount of wood consumed by agents on an agroforestry cell. The quantity of consumable wood on the cell is the quantity of surplus live wood compared to the maximum production level ($75\ m^3$). In this way, the sustainable management of the agroforestry cell is simulated.

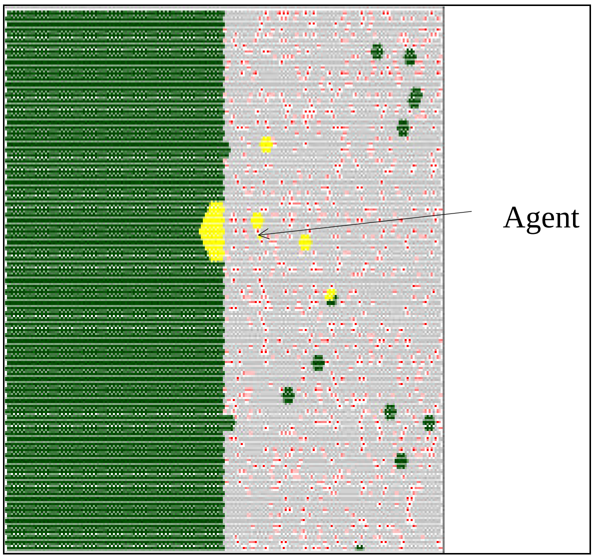

Figure 3: An agent's perception range

3.1.4. Controlling the simulation.

Once the different interacting entities have been defined, the programmes needed to organize the simulation have to be defined. These are as follows:

- Initialization: to initialize the simulation, a simplified map has to be downloaded (Figure 3). This represents the initial spatial situation. The household agents are then positioned on the cropland cells. Each household agent has four members (population = four). The aggregates are then created in order to group together the sets of contiguous forest cells. Lastly, the agents develop their perception on the forest cells that are in their variable wood space within a 2-km radius.
- Control: (Figure 4) at every time step, a number of operations are carried out in order. First of all, the cells calculate wood production. Then, the agents activate the local consumption programme. The cells process the demand. If the agents are unsatisfied, they consume dead wood. The cells process the demand. If the agents are still unsatisfied, they consume live wood. The cells process the demand. Eventually, the cells change state. The cells that belonged to the forest aggregate and which are no longer in a forest state are removed from the forest aggregate. Lastly, for each migration, a new population agent equal to one is created and set up on a cell in a free state. This agent's perception range is calculated.

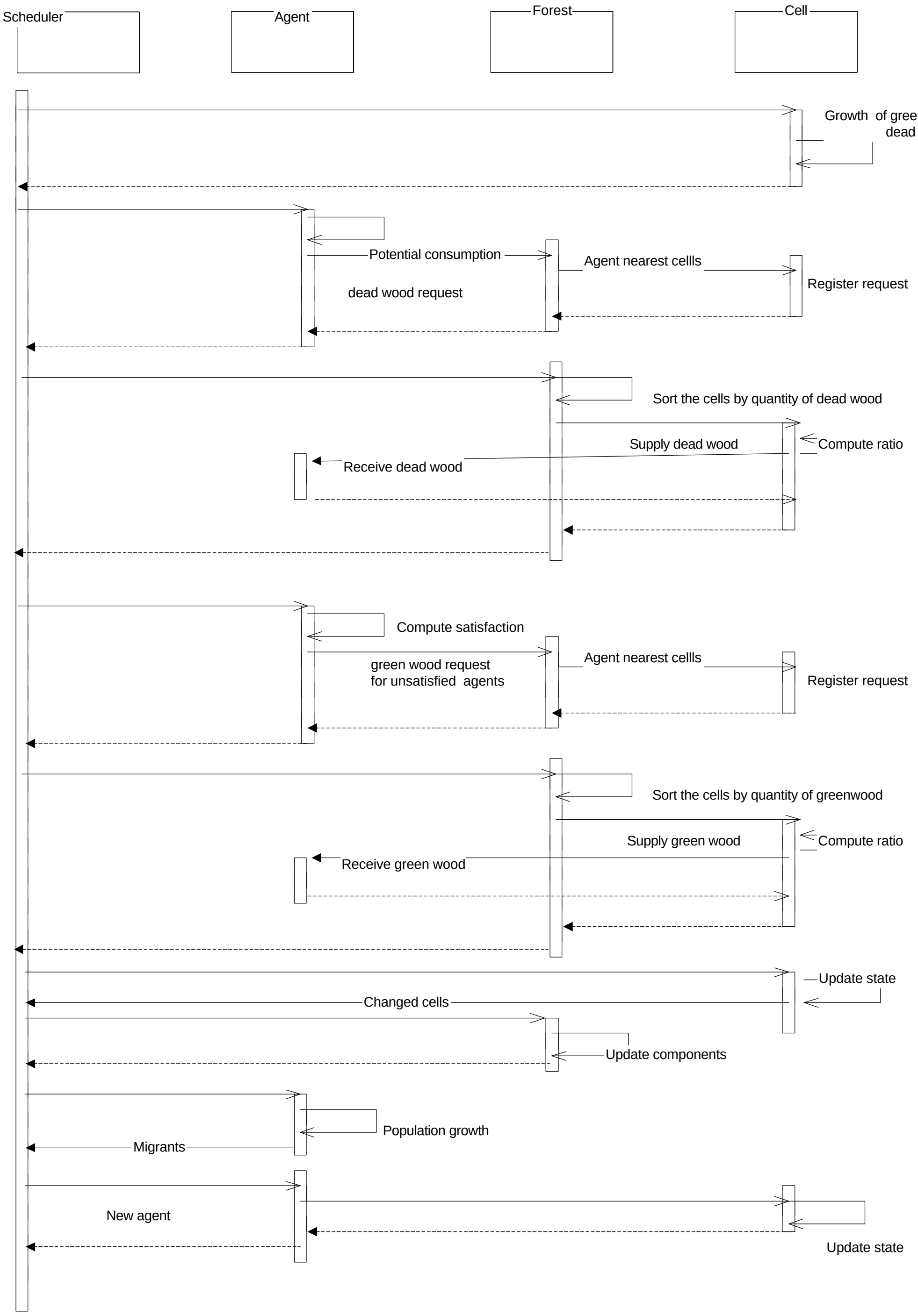

Figure 4: Sequence Diagram

3.2 The scenarios tested

In this article, we test different scenarios. The first scenario (s1) corresponds to the model described above. In the second scenario (s2), simple rules of exchange of use rights are taken into account. Thus, each agent that is unsatisfied with its wood harvest has a look at agroforestry cells in the immediate vicinity to see if there is any surplus wood, before planting trees and transforming their own cell into an agroforestry state. If this is the case, the agent makes a request for wood. In the third scenario (s3), rules governing access are taken into account. Thus, in the small natural forests in the east (right hand side of the map) cutting live wood is prohibited. Finally, a fourth scenario (s4) combines rules of exchange and rules of access.

3.3 Results

We have identified three indicators to compare the results from the different scenarios.

- Consumption/inhabitant: this is the total amount of wood consumed divided by the total population. It reflects the degree of satisfaction. Potential consumption is 1 m³/person.
- The number of forest cells: this measures deforestation.
- The number of agroforestry cells: this is the number of cells where agents have planted trees.
- Population density in the region: this indicates the control of the simulation.
- Results are shown in Figures 5, 6 and 7.

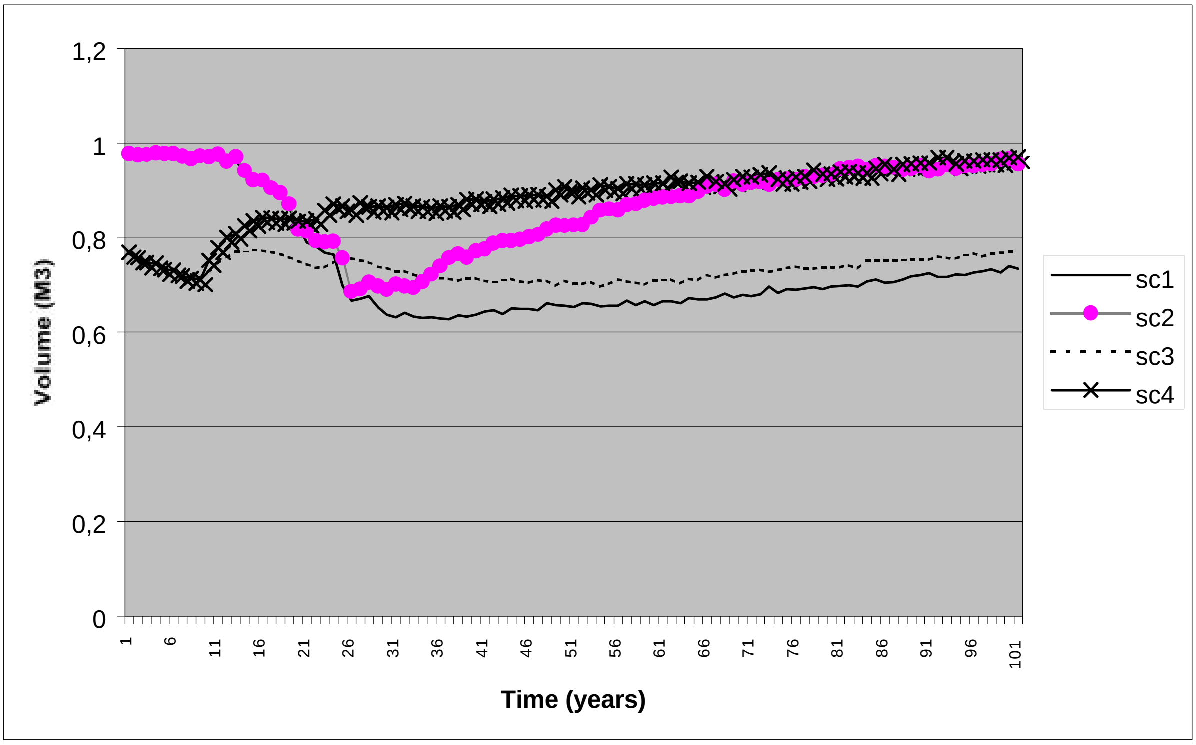

Figure 5: Individual consumption

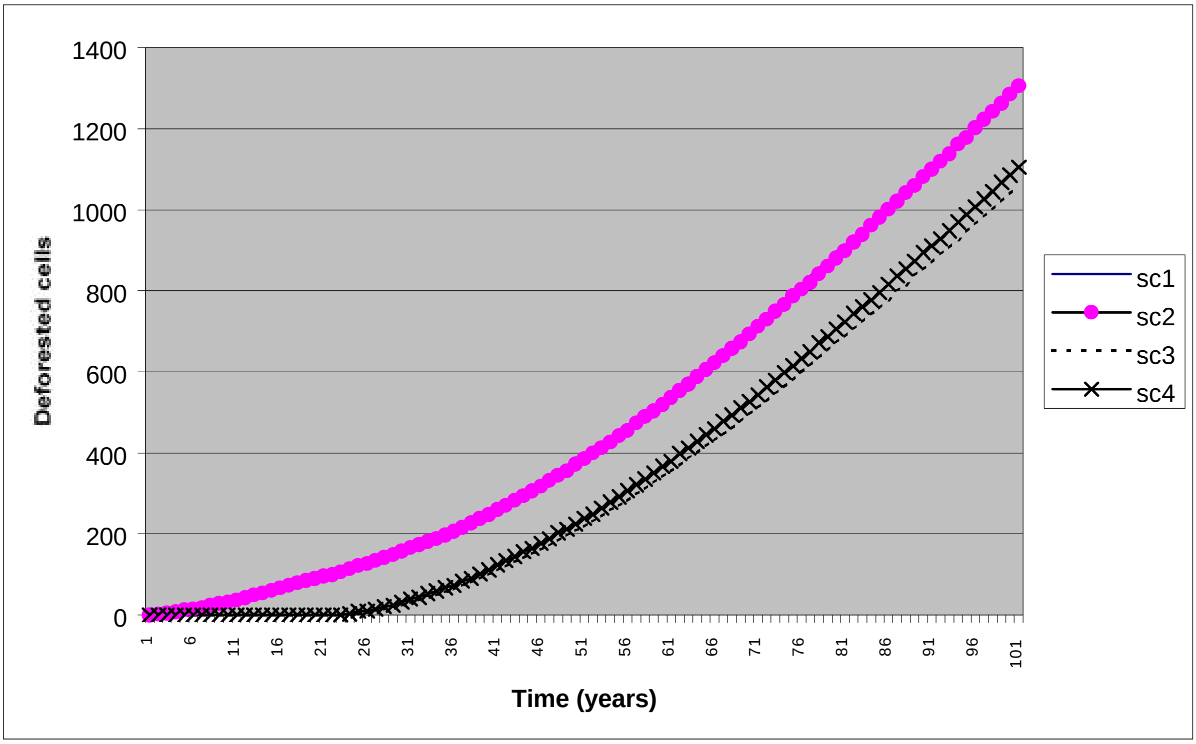

Figure 6: Deforestation: evolution in the number of deforested cells. The SC1 and SC2 have the same results.

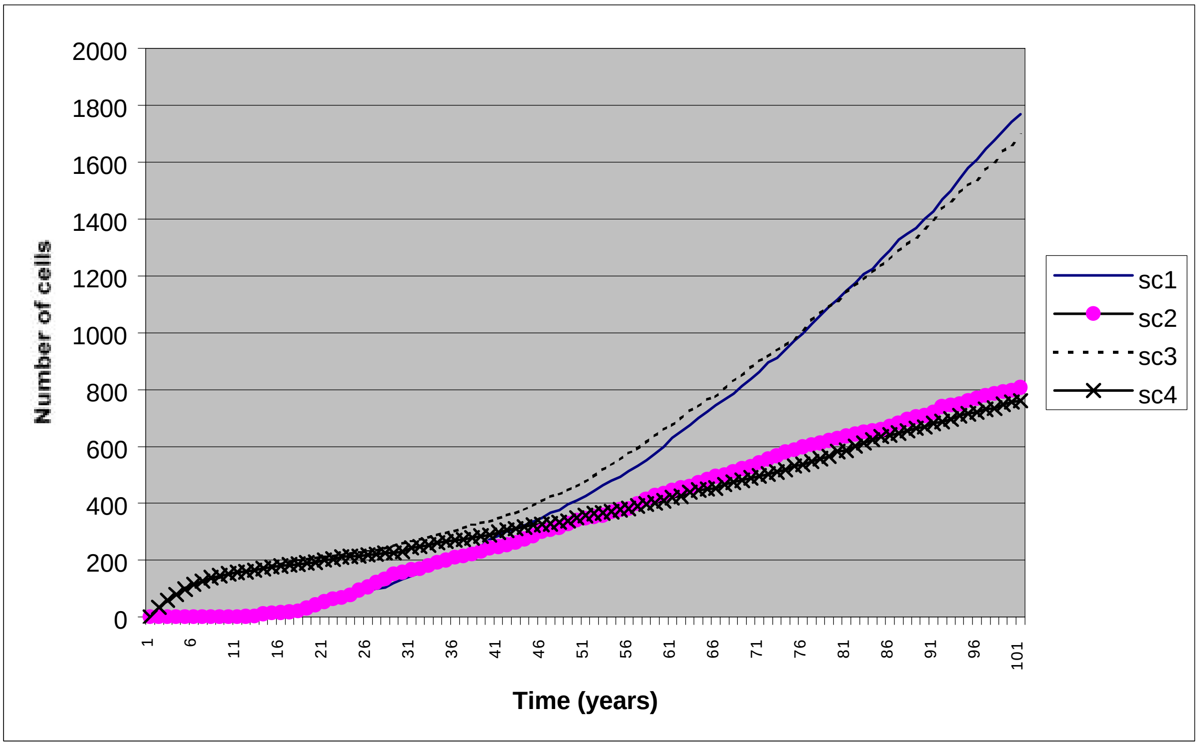

Figure 7: Evolution in the number of agroforestry cells

The figures show the different evolutions which can be divided into two periods, namely, when consumption falls and when it increases again.

The drop in consumption

At the start of the simulation, the simulations can be divided into those with free access (s1 and s2) and those with differentiated access (s3 and s4).

In the case of free access, a few agents use the small forests in the east as a resource and take live wood (Figure 6). Around 100 forest cells disappear which corresponds to the small forests. The small forests satisfy the agents' demand and the agents consume 1 m³ wherever possible. There is a crisis after about 10 years because, once the small forests have disappeared, all the agents in the east (right hand side of the map) find that they are a too far away from the forest. Agents that are able to plant trees on their plots do so (Figure 7). It takes 10 years for the planted trees to start producing, which explains why the drop in consumption levels out after about 25 years.

In the case of differentiated access, the crisis is immediate because there is not enough dead wood in the small forests in the east to satisfy demand. Consequently, the agents plant trees quickly (Figure 7). There is not much pressure on the forest to start with (low population density and wood is taken from a wide area, cf. Figure 6). Therefore, there is less deforestation.

Increase in consumption

The increase in consumption is different in each simulation. In the case of the scenarios with differentiated access (s3 and s4), consumption goes up sooner because trees are planted earlier. However, we observed that the evolution is influenced by whether or not wood can be exchanged. The two simulations involving exchanges (s2 and s4) produce much better results and satisfaction is almost perfect at the end of the simulation. In the simulations without exchange, results from s3 are slightly better at the end of the simulation. This is due to the fact that the small forests in the east that are not cut down continue producing dead wood that the agents collect. We also observed that the possibility for exchange limited the need for planting (Figure 7). We observed that in the cases with differentiated access, deforestation did not occur until year 40. The difference between differentiated access and free access is in the order of 100 cells, which corresponds to the number of cells in the small forests that were felled. The rate of deforestation is the same in the four scenarios.

4. Discussion

In this example, we can see that the spatial distributions of initial resources are combined with stakeholders' behaviour. With this type of methodology, it is possible to study problems that relate to:

1. Fragmented spaces where resources are renewed, which can be observed on several organizational levels.
2. Exchange mechanisms (for goods, services, currency and information) between heterogeneous agents that have different representations.

Complex tools, particularly MAS like the ones described here or by Epstein and Axtell, are effective for representing knowledge of processes and for simulating their interactions.

The results obtained from the above simulations can be interpreted logically by reconstructing the past. However, when the results are examined from a wider perspective, one can see that the observed changes seem paradoxical when considered at a different scale and with static reasoning.

- The simulation with the most forest cover (s1) experiences the most severe crisis (in terms of consumption). This calls into question the logic of matching the supply of natural resources with demand. In fact, in these simulations, once the small forests have been destroyed—their resources are exhausted because of free access—each household independently attempts to deal with the crisis. With the simulations involving exchange mechanisms, fuelwood can be distributed.
- In the simulations, the fact that wood cutting is prohibited in certain places does not exacerbate deforestation in other areas. A number of complex phenomena arise. The small forests that are not cut down provide dead wood. If this is insufficient, agents who are in a position to plant trees on their cells have time to do so and this provides a new source of wood for exchange in future.

Without going into too much detail, one of the milestones of economic theory—which does nonetheless have an important contribution to make to the debate—is the theory of the tragedy of the commons (written by G. Hardin and published in 1968). Hardin suggests that a common resource subject to rational economic forces is condemned to disappear from overexploitation because of free access. This problem can be solved by privatization or by setting up a central authority responsible for managing access to the resources, in other words by controlling access using regulatory or incentive mechanisms (Krutilla et *al).* In our model we can see that controlling access (scenario 3 and 4) delays deforestation but without modifying the rate of deforestation. Another interpretation of resource degradation conversely focuss on the under-exploitation or under investment in natural resources. In this model we can see that differentiate access allow a rapid investment in agroforestry.

But satisfying level of consumption is rapidly reached only when the control of access is associated with exchanges of use rights on agroforestry cells. Thus this investment does not allow a global sustainable consumption when available only to an individual.

A number of authors including Ostrom (1990), Berkes *et al* (1989) and Stevenson (1991) disagree with the privative management theory. They describe the foundations of an institutional approach which involves the application of formal or informal regulatory mechanisms for governing the viability of ecosystems. The word govern refers to representations of stakeholders and is based on a principle of negotiation of use or property rights. The model shows how the issue of exhange of local use rights is of importance in the management of renewable resource.

It can be difficult to put a local approach into practice because of outside interference or restrictions imposed at different levels, therefore, the current trend in research is to support the idea of co-management (McCay and Jones, 1997). Co-management can be applied to resource management within a user group (fishermen) or between several groups that use the same resource for the same purpose (association of catchment areas). Therefore, with other forms of regulation and collective decision-making, it could be extended and applied to the management of resources with multiple uses. This is a question of coordinating the local and global processes involved in managing resources with multiple uses. We consider that simulations using MAS have an important role to play here.

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