Rangeland herd and herder mobility in dry intertropical zones: multi-agent systems and adaptation

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François Bousquet*, Patrick d'Aquino, Juliette Rouchier*, Mélanie Requier-Desjardins*, Alassane Bah***, Richard Canal***, Christophe Le Page***

*Cirad Tera Ere Green

Campus de Baillarguet, BP 5035, 34032 Montpellier Cedex France

{bousquet,rouchier, requier, lepage}@cirad.fr

** Cirad Tera, PSI, BP 744 Saint Louis, Sénégal

daquino@telecomplus.sn

*** Ensut/Esp, Dakar, BP 5085 Dakar, {abah, rcanal}@ucad.sn

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1. Introduction

In the Sahel, the question of interactions between rangeland herding practices and the environment lies at the heart of the debate concerning sustainable development (Milleville 1989 and 1992, Bernus 1990, Behnke and Scoones 1992, Claude *et al.*1991, Boutrais 1992, Blanc-Pamard and Boutrais 1994, Collectif 1995, Thebaut 1990 and 1995). There is disagreement about the question of Sahelian herd *mobility,* which remains necessary for some while for others it is outmoded, and which is judged in terms of its environmental impact. There are also many questions regarding the influence of socioeconomic policies on herder behaviour.

Interventionist policies for settled development of rangeland livestock production are confronted by highly mobile systems, adapted to environmental variations in time and space. Indeed, faced with the economic and climatic constraints of the region, the intensification of Sahelian livestock production has so far met with failure (Benoit 1984, Thebaut 1995) as demonstrated by the catastrophic livestock losses around certain boreholes with abundant water supplies in the 1980's.

Experts have widely diverging opinions on key points which are essential for understanding and evaluating rangeland herd mobility. They find it difficult to assess the economic and social reasoning of herders or the adaptive value of rangeland herding practices in a changing and diversified environment. Indeed, researchers are confronted by highly complex systems which are very difficult to analyse due to a lack of knowledge concerning:

1. the diverse behaviours of resource users, combining several cycles of mobility (daily, seasonal, multi-annual) in an environment where resource availability is distributed over space and time;
2. the impact of uses on the state of the resource and the variations in these uses according to the users' perception of these resources and their interactions with each other.

Scientists build models to study systems. They have often been successful in solving problems of design and control. In the field of renewable resources, researchers in mathematical bioeconomics use models which aims to identify the sustainable yields of a resource. A system of differential equations represents the ecological and economic dynamics and field data provides parameter values. Then through the control theory methodology solutions for outcomes such as the maximum economic yield are proposed to a 'decision maker'. Thus informed, the decision maker is supposed to be able to take better decisions.

To understand highly adaptive systems—such as Sahelian rangeland systems where herders are continuously having to adapt to prevailing circumstances—models are needed that reflect this adaptive capacity. We are confronted with a complex system, a system consisting of a large number of agents that interact with each other in various ways. Multi-agent models of these complex adaptive systems (CAS) provide one such modelling framework (Holland 1995). In these models the agents change their actions as a result of the events in the process of interaction. The behaviour of the whole system depends on these interactions between agents which can be represented in a model. The aim of the modelling experiment is not to represent the whole system. It aims at building and testing theories. Complex dynamics may emerge from simple rules. Herders are not the sole actors involved in the management system considered in this paper. Public administration, NGOs, researchers, sedentary peasants, and migrants have different representations of the system. The management of the resources is a collective learning problem. Models may be used to focus discussions on cause and effect connections between behavioural and interaction rules and the rangeland dynamics. Thus the goal of these models is to assist and inform adaptive management and policy decision-making in complex systems, rather than to proscribe and direct a supposedly optimal solution.

In order to illustrate these ideas, we performed two modelling experiments on the theme of mobility as a means of adaptation. The first experiment studies the relation between movement strategies and the dynamics of resources in space, while the second studies the social relations maintained by herders in order to obtain access to rangelands and water. To this end, we used the multi-agent modelling method. This method is based on the representation of entities which interact directly with each other or via the environment. In this article, we present these methods and describe the two modelling experiments. We conclude with a discussion on the use of such models.

2. Multi-agent systems

Multi-agent systems offer a modelling method based on the principles of distribution and interaction (Bond and Gasser 1988, Ferber 1995, Lesser 1995, O'Hare and Jennings 1996). To model a complex phenomenon, different interacting entities with specific behaviour patterns are represented. The computer entities (agents) perceive their environment and are able to act upon it, are able to communicate by sending messages and to make representations of the world. This structure reflects a bottom-up approach to the representation of reality. Knowledge is represented at the microscopic level and emergent phenomena are observed at the macroscopic level.

Widely used in telecommunications and distributed systems and often used to represent spatial dynamics, multi-agent systems are used increasingly to study problems in ecology (Folse 1989, Hogeweg 1990, Meyer 1991, Le Page 1996) and social sciences (Bura 1994, Gilbert 1995, Doran 1995, Conte 1997) as well as in the area of renewable resources (Bousquet 1994, Epstein 1996). Some researchers focus on the simulation of biophysical processes, others on social dynamics. Used as metaphors, the models pose questions that are common to both disciplines. How do social norms develop in response to social and environmental changes? What are the implications of changes in social norms for the resource base? In the research we are conducting on common property resources, it is the co-ordination between actors about appropriation and uses of these resources that we consider. Each actor, individual or group, acts on the environment and communicate with the others about these actions.

Multi-agent systems are often used to represent spatial dynamics. A number of tools are now available to represent these models, such as Swarm (Burkahrt 1994), for example. We used an environment called Cormas (Bousquet 1998) which divides the description of the artificial world into two parts, modelling space and resources on the one hand and the movement and communication behaviours of agents on the other.

To study the adaptation of populations of agents to an environment, many researchers apply an evolutionary process driven by the reproduction of populations. This is the domain of complex adaptive systems (CAS) (Belew and Mitchell, 1996). Holland, one of the pioneers of genetic algorithms, proposes a simulation environment called Echo based on the principles of multi-agent systems and genetic algorithms (Holland, 1995). He thus shows how tit for tat strategies are liable to emerge in populations of agents which play the prisoner's dilemma game. Under the name of genetic programming, Koza (1991, 1994) constructs populations of programs to which the operators of reproduction and crossing are applied. Examples, such as the search for food by ant populations, demonstrate the emergence of behaviours adapted to the environment. Certain applications highlight the merits of this type of tool for studying the relations between resource diversity and adaptation. In the field of economics, Matos (1998) demonstrates the importance of a mixture of strategies among a set of sellers and buyers whose aim was to find the best negotiation strategy in different types of environment. In theoretical biology, Le Page (1997) also shows the advantages of mixed reproduction strategies in a variable environment.

3. First experiment: mobility patterns in heterogeneous and dynamic environments

The objective is to determine the mobility strategies adopted by herders in response to resource variability in space and time.

3.1 Modelling

1. Space and resources

The rangeland environment is represented by a grid (Fig. 1) containing five specific resources, in proportions freely modified by the model user. Four of these are resources in the conventional sense and their regular renewal depends upon the weather; water, "average" rangeland and two scarcer food sources called resources A and B (which might, for example, represent specific protein sources or a salt deposit). The fifth resource is a "social resource", the village.

2. The agents

The agents represent the herd-herder pair, whose behaviour is characterized by consumption of resources and movements. As in most multi-agent systems, it possesses capacities for representation, memorization and communication. The expert's perception is tested in:

- The qualitative assessment of the herd's needs: two values are associated with each resource. The first value, called the "level", is variable and represents the agent's degree of satisfaction with respect to the resource. It decreases if the agent does not have regular access to this resource. The second variable, the "critical threshold", is fixed. If the level corresponding to a resource reaches the critical threshold, the need for this resource becomes urgent and the agent must act accordingly.
- The various herd movement patterns that can be adopted to satisfy its needs. According to what reasoning does the herd consume (or must it consume) the different resources

available on the land? Agents may or may not be capable of memorizing the position of resources. Two memorization modes are proposed, local or global, depending upon the agent's degree of perception. Agents may or may not possess the ability to communicate. If they are able to communicate and possess a memory, they may exchange all or part of the content of this memory. If they have no memory but can nevertheless communicate, they exchange only the position of the resources they perceive at the moment of communication. The analysis criteria for simulation results are as follows (over a cycle of one to ten years): herd survival with or without drought, emerging degree of mobility and territoriality, state and resilience of the environment.

3.2 Simulations and strategies

The experiment is divided into three stages. In the first stage, the patterns of herd movement in space (called "strategy" in the simulation) for the consumption of the different resources are defined. These strategies are compared to real world strategies observed in the field to ensure their validity. When realistic situations of herder-environment interaction have been selected, the second stage can commence. In this stage, the various factors liable to influence the variability of existing herder-environment interactions are identified and evaluated. Environmental factors such as quantity and distribution of resources or frequency of droughts, anthropic pressure factors such as the number of herds or consumption behaviour and factors of social context such as the type of communication between herders or the degree of attachment to village are dealt with. In the third and final stage, the impact of different possible development and intervention policies (including collective rules for use and appropriation) are evaluated.

3.2.1 Initial strategies

The experiment is currently at the end of the first stage. Initially, three behaviour patterns or strategies were developed (Bah 1996). These strategies were identified through expert opinion, based on many field observation and through the knowledge of the computer scientist who is a member of the Peul ethnic group (the herders). According to the first pattern (strategy 1), when the agent is not in critical need of resources, it seeks to consume the resource that will soon be in short supply. On the other hand, if the agent has several critical needs, it will seek among these critical resources the one with the greatest positive impact on its health. If this resource is not available in the environment, it will search randomly for one of the other resources corresponding to a critical need. We have called this first pattern "hierarchy-impact", as the agent classified its needs in hierarchical order according to their impact on its health. The second pattern (strategy 2) have been called "hierarchy-time". According to this strategy, (a) when the agent is not in critical need of resources, it consumes the closest available resource, whatever it may be and (b) the agent seeks to consume the resource that will soon be in short supply (the lowest threshold). On the other hand, if the agent has several critical needs, it will seek among these critical resources the one for which the need is most long-standing. If this resource is not available in the environment, it will search for one of the other resources corresponding to a critical need. The third implemented pattern (strategy 3) can be described as opportunistic. According to this strategy, when the agent is not in critical need of any resources, the herder causes his animals to eat the closest available resource, whatever it may be. Similarly, if the agent has several critical needs, it will seek among these critical resources the one which is located in closest proximity. If the resource is not available in the environment, it will search randomly for one of the other resources corresponding to a critical need.

We have compared by simulation these three strategies from a static point of view. In the experience related here the strategies do not change. Agents adapt to their environment by improving their cognitive model of the environment. They improve their knowledge of the resource. There is also a collective adaptation through the environmental feedback. In other experiments we are preparing the strategies will evolve, by using combination of MAS (multi agent systems) and genetic algorithms.

The behaviours in space of herds following these different strategies highlight the effectiveness of the "opportunistic" pattern when the environment is so unfavourable that certain needs cannot be satisfied whatever the strategy adopted (certain resources are too scarce in the existing environment with respect to the stated needs). On the other hand, when theoretical viability solutions exist in the space (scarce resources available in just sufficient quantities), it is the "hierarchy-impact" strategy which becomes most effective. However, when the researcher introduces extreme conditions (severe drought) he observes that, whatever the chosen strategy, the herds behave in a way which he qualifies as aberrant: when the pastures around the water supply point are exhausted, the herds stay on these pastures, not daring to move further from the water supply than the distance they can cover without needing to drink . Hence, most of the animals die of hunger (around 5% survival on average). The only conceptual solution which enables the herds to escape from these dead-end situations around the water supply points is for them to decide to *take risks* by venturing into an *unknown environment* without knowing if their needs will be satisfied.

3.2.2 A new strategy: viable sub-spaces.

This simulation experiment raises new questions. The simulation clearly highlights the fact that in a drought situation the herder must decide to move to an unknown environment and take risks which cannot be assessed beforehand. What criteria does he use to limit these risks? What measures could he take to minimize the risks incurred? The design of the strategies in the simulation and beyond that, the understanding of herder behaviours, is thus enhanced, since two questions must now be answered: ***Under what conditions must the herder decide to take risks and to leave his familiar environment?*** When the conditions are not extreme, we have seen that "reasonable" behaviours, without any risk-taking, are effective. But in a context as variable and unpredictable as the Sahelian zone and its seasonal cycles, what criteria can be used to decide that the situation has become extreme and that it is time to move away from the habitual transhumance cycle? At what moment must prudence be replaced by temerity? ***Once this exceptional transhumance has been decided, what new pattern of movement will be adopted?*** Which directions will he take? Which criteria, in an extreme situation, will he use to select the new zone to settle in? What viable situations can the herder still hope to attain? The herder (and the researcher) must integrate the **concept of viability** of an environment: how can a viable rangeland environment be defined, especially during a period of drought? What indicators can be used as a basis for this definition? How can information about these indicators be obtained before or during this crisis period?

This led us to the following conceptualization of the behaviour of herders when confronted by a critical drought (strategy 4): the herder must be "worried". Being "worried" means asking the question "am I in a viable environment"? To answer this question, the agent can use two types of indicator: direct indicators, i.e., the presence and the state of the resources in its environment, and indirect indicators, such as the evolution of its own state of health. The evolution of state of the health enables the agent to assess the quality of the environment. Once the agent has decided to "flee", it goes to other environments which it knows to be more viable. It uses its knowledge of the region, then its communication networks to update this knowledge (current state of resources). We had to define the notion of viability precisely: here, we consider a viable situation to be an environment in which the resources which are needed for the health of the herd occur within the distance from a water source which can be covered without needing to drink. Our notion of the viability of an environment limits the area to a circular zone around a water supply point.

4 Second experiment: modelling of relations between transhumant herders and the sedentary population

In the second model, herding practices are viewed from the point of view of the relations between communities: we are interested in the herders' capacity to obtain access to pastures and water. Unlike in the previous model, the resources are not open access resources. The ability to feed the herd is therefore dependent upon the relationship between the herder and the sedentary population (individuals or local authorities) who own the resources.

4.1 The Model

This model is not defined in spatial terms. The agent classes are all social agent classes. Three agent classes were defined in this system: transhumant agents, sedentary agents and villages. The first two classes make requests to use two resources: water, managed by the villages and forage managed by the sedentary agents. Access to each is defined by an agreement expressed in terms of cost. These are one to one agreements. At the end of a negotiation, an exchange is decided: money for forage units or a right of access to water. The act of negotiating also represents a cost. As the number of requests is limited and money is obtained by the sale of animals, the choice of these requests is important and decided on the basis of two criteria:

- either the transhumant agent goes to see the agents offering a low access cost - this is an "economic" tendency to reduce costs to a minimum;

- or it prefers to strengthen relational links, following a "socializing" tendency to maintain a social network.

At the end of the year, the transhumant agents deduct the growth of the herd from the quantities of resource obtained. They then evaluate the quality of their relations with each of the sedentary agents and villages encountered (by comparison with their expectations regarding these relations). They then make gifts to deserving agents. All the sedentary agents then do their accounts, both in monetary and relational terms. The individuals also check whether enough animals have fertilized their field without overgrazing it, and this makes it possible to assess the state of degradation of the resource. The villages draw up monetary accounts only.

4.2 Simulation

The simulations represent a succession of years in which the population size, number of possible meetings, access and communications costs, animal sales price and criterion chosen by transhumant agents (pay as little as possible or strengthen links) are fixed at the outset. We then observe the survival capacity of the transhumant agents on the basis of these various parameters and the image of the others constructed by each agent.

At the time of writing, the simulations have not yet been performed. The hypothesis which will be tested is that socializing behaviour leads to greater chances of survival over the long term, even though it may be less advantageous over the short term. To this end, we will compare the transaction costs associated with both types of behaviour, economic versus social, over the short, medium and long term.

5. Future developments

To examine the problem of adapting rangeland herding practices to fluctuating environments in the dry intertropical zones, we have developed two models which use the multi-agent methodology. The first model places emphasis on the *individual strategies* of agents in their movements and on *their interaction with their environment and other agents.*. Adaptation is a factor in the agents' representation of space: they must construct representations of viable zones. They interact via the environment since they consume resources. They coordinate their actions indirectly through differentiated use of space and information exchange. The second model places emphasis on the *economic and social relations* for access to resources between agents with varied behaviours. Coordination may be mercantile, via the calculation of a financial utility, or social via the desire to strengthen social links. Our task is to measure the relative efficacy of these two modes of coordination in enabling the agent to adapt to fluctuating environments. Whether it be links between agents and their land for the first model or links between agents themselves for the second model, it corresponds to an overall vision of collective adaptation to a fluctuating environment through the creation and preservation of a set of links. We believe that these methodologies provide an effective means to address these questions.

We believe that these various conceptual definitions provide the researcher with rich insights to aid the analysis of Sahelian herders behaviour and for the evaluation of their principal constraints. This information will be useful for further research, such as the evaluation of effective support measures for these herders. By moving on from field expertise to multi-agent simulation, we are able to conceptualize more accurately the perception of herder behaviours and hence to define more clearly the support that should be provided during these critical periods.

6. **Research models or applied models**

In this paper we propose an approach to the use of multi-agent simulation models. How may a model of behaviour be used in decision making process? In this section of the paper we pose some preliminary thoughts on how these models might be used to assist in decision making.

One of the classic uses of simulation is for prediction, but this is not the option we have chosen. The very long term cannot be predicted in the economic and social field, though it is partially decidable. This is the hypothesis underlying the "patrimonial approach" (Ollagnon 1989, de Montgolfier & Natali, 1988). "Because the very long term is beyond the scope of prediction, if we wish to take it into account in the analysis of environmental problems, we must give ourselves very long-term reference points or objectives to guide the possible or impossible pathways of development. The long-term approach must inevitably be based on a scenario" (Weber & Bailly, 1993). It is on the basis of a shared conception of how the present situation should evolve that actors are able to "decide" very long-term objectives, on the basis of which the scenarios which enable them to be reached can be discussed. The entire mediation approach presupposes the establishment of an initial situation, in Rawls' sense, in which the actors are clearly informed of the issues which divide them and of their common dependence upon a solution to the problem at the base of the mediation process. The challenge of the initialization phase is to enable actors to express their perceptions of the present situation and of its evolution. When a "map of perceptions", all equally legitimate and equally subjective, has been established and discussed, the actors can be asked to discuss the acceptability of prolonging existing trends.

How can simulations be involved in this process, i.e., how can they help actors to govern ? We are seeking to develop the idea of companion modelling using multi-agent systems. The ideas which follow constitute an approach which is currently being implemented but which, as yet, has only been partly tested. Though it is doubtless original in its use of multi-agent universes, it is an approach which has already been used by several researchers whose work has served as a basis for our studies (eg. Ostrom 1990 Burton 1994). Much work has been done by Mermet (1992) and Piveteau (1994) on the relation between the patrimonial approach and the placing of actors in an experimental situation through role playing.. Our thought framework is close to these authors and we propose to include the modelling approach with multi-agent systems within this framework. This involves a number of stages:

- Construction of an artificial world. The first classic stage, involving one or more researchers, is to gather information on the system under study. We suggest that field work and modelling be performed in unison. The task is to identify the different actors and perceptions and to use multi-agent universes for modelling. Faced with a highly complex world, multi-agent universes provide a means to identify the most acceptable form of simplification by focusing questions on problems of representation, communication and control. Simulation raises questions to guide field observation which in turn provides new understanding and data to improve the model.
- The second stage is a restitution stage which could also be referred to as validation of the cognitive model. The aim is to test the model proposed for the decision-making process. It involves a thorough analysis of the representations and interaction processes between agents. Indeed, it is difficult to explain what has been "put into the machine". On the other hand, it is possible to put an actor in the situation of the agent who is in the machine, with the hypotheses of representation, communication and control which constitute the model. To perform this operation, we propose to use the role-play methodology tested by the authors mentioned above. The artificial world is evaluated by plunging the actors into it, i.e., by creating a world similar to the model. These actors may be actively involved in the management system as users of the resource (farmers), regulators of this management system (managers or administrators) or observers of the system (researchers). Does the artificial world inhabited by these actors resemble the real world ? The aim is to validate a simulator in the same way as, for example, a flight simulator. A good flight simulator incorporates the same components of the decision-making process as in reality, rather than simply reproducing an actual flight. This stage may be included in the initialization phase of the patrimonial approach as it provides a means to establish a map of the various types of actor, the different perceptions and interactions, and to make them into shared knowledge.
- The third phase is the simulation phase. Simulation shows how the dynamics of the system arises out of interactions between actors with different weights and representations. We can divide this phase into two sub-phases. Initially, the simulation can be performed in the form of a role play, which enables actors to validate the fact that it is indeed in the interactions between different representations that the motor driving the dynamics of the system is to be found. This first sub-phase also brings to light the different scenarios that are worth testing. Then, once this phase has been completed, the multi-agent model can be used to make simulations based on different scenarios. Simulations, both "in ludo" and "in silico", are also involved in another phase of the patrimonial approach in which, after long-term objectives have been defined, the various scenarios liable to lead to these objectives are tested and their results discussed.

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Figure 1. The rangeland environment as represented in the simulations.