MULTI-AGENT SYSTEMS COMPANION MODELING FOR INTEGRATED WATERSHED MANAGEMENT: A NORTHERN THAILAND EXPERIENCE

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ABSTRACT

Integrated watershed management means a collective management of the land, reconciling ecological dynamics and social processes to ensure a sustainable and equitable use of renewable resources. Because different stakeholders have different representations of a local agricultural system, its integrated management can be seen as a collective learning process. New types of models, closely articulated with field work and other participatory tools, can be used to facilitate such collective learning. They are particularly useful for elucidating relationships among agent behaviors and their interactions and resource dynamics at different levels of organization.

This paper describes and discusses the development and preliminary field testing of such a companion modeling approach, based on the use of multi-agent systems (MAS) associated with role-playing games. Companion modeling supports on-farm, interdisciplinary, and action-oriented participatory research to facilitate dialogue, shared learning, negotiation, and collective decision-making among multiple stakeholders. The principles of this approach, the characteristics of agent-based models, and associated role-playing games are explained. Their validation and use with stakeholders to manage renewable natural resources are also presented. The article is illustrated by an ongoing case study to improve steep-land management by limiting land degradation in rapidly diversifying and market-integrated farming systems of Akha villages in upper northern Thailand.

Fieldwork and modeling activities are seen as complementary, and they are closely linked in an iterative way. The collective construction of a common artificial world with stakeholders leads to the emergence of a shared representation of a complex system and the concrete problem to be examined. Later, such a common representation can be used among stakeholders as a coordination and negotiation support tool to identify and to assess scenarios of desirable futures. On the basis of a shared understanding of current systems dynamics, this approach helps to identify acceptable rules for an improved regulation of collective uses of land resources.

When a policy of decentralization of natural resource management is implemented, companion modeling can be used to integrate knowledge, stimulate dialogue, and establish adapted coordination mechanisms regarding multiple uses of the land by multiple stakeholders, but also to assess suitable innovations and desirable scenarios of land-use changes for the future.

INTRODUCTION

Integrated watershed management means a collective management of the land, reconciling ecological dynamics and social processes to ensure a sustainable and equitable use of renewable resources. Because different stakeholders have different representations of a local agricultural system, it is important for them to take into account and to understand such differences. It is possible to look at integrated watershed management as a collective learning process aiming at reaching an agreement on rules to be followed by all concerned stakeholders to favor the co-adaptation and co-viability between natural and social dynamics. We think that such an agreement can be brought about through the confrontation of stakeholders' various points of view.

The complexity of coordination and negotiation processes among multiple stakeholders exploiting a common agroecosystem, such as a watershed, raises methodological questions. To deal with the increased complexity and rapidity of changes in Montane Mainland Southeast Asia (MMSEA) watersheds, as well as their unpredictable outcomes, new types of models can be used in association with other tools to facilitate such collective learning. These models belong to the emerging area of the science of complexity. In a given watershed, complexity is created by the heterogeneity of the environment, landscapes, and society and by the diversity of interacting processes that are taking place among different natural and human entities. In the field of integrated natural resource management (INRM), understanding interactions between natural and social dynamics is of paramount importance. Natural dynamics are made of numerous interwoven biophysical processes, involving different resources at different spatial and temporal scales. Social processes involve decisions made by different stakeholders at various levels of orga-

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nization, ranging from individuals and local communities occupying the land and exploiting its resources to large development-oriented or policy-making institutions. A promising modeling approach of complex systems postulates that simple rules of organization and functioning can be identified from the apparent complexity of the system, and key structures and rules of evolution can be elucidated to better understand and manage the dynamics of such systems. Particularly, such models can be useful for understanding the relationships among agent behaviors, their interactions, and the resulting agroecological dynamics at different levels of organization (field, farm, watershed). Based on a prior understanding and modeling of the natural and agronomic dynamics, finding a way to produce acceptable social rules for an improved regulation of collective uses of land resources is a major question in INRM.

But what kinds of models should be used for such a purpose? And how can we use them with multiple stakeholders? This article proposes the use and the development of a "companion modeling approach" (Bousquet et al. 1999). It is illustrated by a case study on steep-land management in diversifying and market-integrated farming systems of Akha villages in the highlands of northern Thailand.

A COMPANION MODELING APPROACH BASED ON MULTI-AGENT SYSTEMS (MAS)

Recently, significant progress has been made in the field of research on simulating societies in interaction with their environment (Epstein and Axtell 1996; Gilbert and Troitzsch 1999). Innovative approaches, such as multi-agent systems (MAS), can create virtual societies (Weiss 1999). MAS are computational systems in which various autonomous agents interact in a given environment (fig. 1). MAS originate from the computer science field of distributed artificial intelligence (DAI) and rely on the technology of cellular automata. They are based on the principles of distribution, interaction, and control (Ferber 1999). An agent is a computerized process, something between a small program and a robot. Agents can be of very different nature. Each of them is modeled with its own perceptions and decision-making rules, modes of communication (with other agents and the common environment), and control (synchronization of hierarchical relationships among agents). An agent is characterized by specific attributes and a set of behavioral rules. An agent is able to act locally in response to stimuli from its environment or communication with other agents (Bousquet et al. 1999). Agents are said to be autonomous because they have a built-in capacity to adapt when their environment is changing. To understand how various independent processes in direct competition are coordinated is a key issue in MAS modeling and simulation. How are collective structures and rules set up in systems based on agents with different capacities of representation, which are exchanging information, goods, and services, drawing up contracts, and all acting in a dynamic environment that responds to their actions? How do they emerge from individual actions in a bottom-up way? (Bousquet et al. 2001).

Agent-based modeling and MAS simulation are being increasingly used to deal with ecological and socioeconomic issues arising from the management of scarce resources, with multiple uses by multiple users. When such approaches are applied to NRM problems, as in modeling situations of conflict among stakeholders, the effects on the resource dynamics of the interactions among different agent behaviors and the associated feedback effects can be simulated and tested. Modelers use these methods to create computer representations of dynamics observed in the field. Therefore, in a companion modeling approach for examining practical NRM problems, field work and system modeling are two complementary activities that are closely interlinked in an iterative way to produce shared representations of the system to be managed.

Recent field experiences have demonstrated the effectiveness of the use of such models to support on-farm, interdisciplinary, and action-oriented research in various contexts and ways (Aquino et al. 2002). Usually, the outputs of this kind of research are used to facilitate dialogue, shared learning, negotiation, and collective decision-making among multiple stakeholders studying a concrete

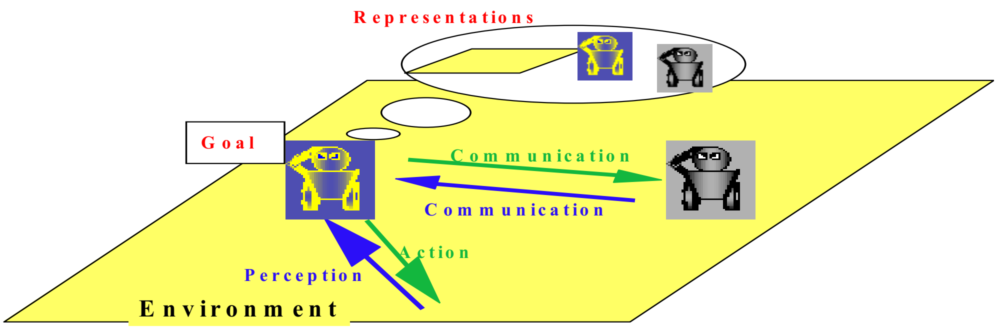

***Fig. 1.* General representation of a multi-agent system. After Ferber 1999.**

INRM issue (Barreteau and Bousquet 2000; Lynam et al. 2002). In a companion modeling approach, this can be done through the collective construction of a common artificial world leading to the emergence of a shared representation of the complex system and problem. In association with other tools, MAS models can be used as a mediating tool to achieve a collective agreement among diverse stakeholders on the watershed organization and dynamics. Later on, this common vision can be used to facilitate stakeholders' coordination and negotiation mechanisms to improve its management. For example, simulation tools can be used to identify and assess a scenario toward desirable futures of the system with all concerned stakeholders. Different options can be rapidly and interactively defined, simulated, and discussed to facilitate the emergence of socially and ecologically acceptable courses of action through improved stakeholder communication and interactions (Röling 1996).

Closely articulated with MAS models in the companion modeling approach, role-playing games are used to produce new knowledge, to help build MAS models, and to validate them (fig. 2). Depending on the circumstances,

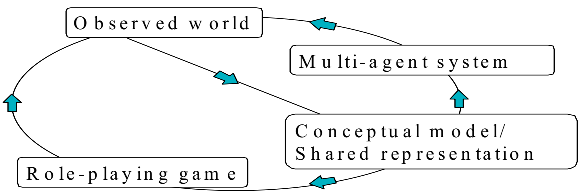

***Fig. 2.* Linkages between the reality and interactive tools in the companion modeling approach**

the linkages between these two interactive tools can vary (Aquino et al. 2002).

Therefore, the complementary functions of MAS models and associated role-playing games are an original methodological feature of the companion modeling approach. These tools present many parallels facilitating their association (Table 1). Linking them is also made easier because both of them operate through a gradual and iterative process of learning-by-doing.

Table 1. Correspondence Table Between Role-Playing Games and Multi-Agent Systems Associated in the Companion Modeling Approach

Role-Playing Game	Multi-Agent Model
Players	Agents
Roles	Rules
Turn	Time step
Game set or playing board	Interface or grid
Game session	Simulation

The use of role-playing games derived from more complex models through simplifications facilitates the communication of the results of agent-based computer simulation to stakeholders. It helps empower them to use such powerful tools when looking for "solutions" to a concrete NRM problem. If it can take half a day to play several years of a scenario with the role game, a given set of system management rules can be simulated by the MAS model far more rapidly. Beyond their potential for improving interactions among local stakeholders and for elucidating the effects of their decisions on the resource base, this methodology can also help to identify and assess suitable scenarios and innovations leading to desirable future situations.

A MULTI-AGENT MODEL TO UNDERSTAND INTERACTIONS BETWEEN CROP DIVERSIFICATION AND LAND DEGRADATION AT THE WATERSHED LEVEL

In montane northern Thailand, as small-scale highland farming is being rapidly integrated into the market economy, the risk of increasing land degradation is a major problem in this fragile and heterogeneous environment. An increasing number of individual or collective stakeholders are presently interacting in sloping-land agriculture, all of them having their own land-use strategy. We think that the emergence of an ecologically sustainable and socially equitable type of highland agricultural development will require improvements in the way these diverse stakeholders coordinate their actions in their common environment.

As in other neighboring countries, a process of decentralization of the management of natural resources toward local communities is under way. We are proposing to use our companion modeling approach to facilitate the dialogue and the coordination mechanisms on land-use changes among local stakeholders in such highland watersheds. Later on, possible future scenarios for highland agricultures similar to the one observed in the villages where intensive field data collection was conducted could be jointly defined and assessed with the concerned players. In the process, we could also aim at assessing the influence of social behavior and farmers' practices on the effects of the government environmental policy in these remote areas.

This case study is being developed by several collaborative research and development partner institutions having complementary comparative advantages: Cirad and IRRI, the Multiple Cropping Center of the Faculty of Agriculture at Chiang Mai University, the Department of Public Welfare, and the farming communities in Mae Chan and Mae Fah Luang districts of Chiang Rai Province. They also represent successive links along the research-development continuum. The local agricultural system is displaying a rapid diversification of agricultural practices, associated with an extensive socioeconomic differentiation among farming households. These profound rural transformations are powered by strong driving forces, such as the integration of the local economy into commodity and labor markets, the expansion of communication infrastructure, population migrations, and national policies on environmental protection (Trébuil et al. 2000).

Purpose of the Model

Based on earlier in-depth, on-farm surveys at the field, household, and watershed levels carried out during two years in two Akha villages (Trébuil et al. 1997; Turkelboom and Trébuil 1998), a prototype agent-based model was initially built. Its objective was to integrate knowledge for a better understanding of the interaction between crop diversification and land degradation at different scale levels, from small homogeneous units in cultivated fields with complex slopes to the whole village watershed, through the functioning of the main different types of farming households. This simulation model provides a spatial representation of the effects of farmers' actual cropping practices on the risk of land degradation by concentrated runoff.

Conception and Structure of the Model

A detailed description of this MAS model is given elsewhere (Trébuil et al. 2002). Its general structure is displayed in Figure 3. The MAS modeling approach was selected to integrate local and scientific knowledge on land management obtained at complementary spatial and social levels of organization and operating at different time scales (single rainy event, crop cycle, crop succession, long-term trends in land-use changes). The general model structure and operating rules are sufficiently generic to allow its use at various sites where watershed characteristics and interactions between ecological and social dynamics are similar.

This conceptual MAS model provides an agent-based representation of the village watershed in which different interacting entities, with specific patterns of behavior, perceive (partially and differently) their common environment and act on it to achieve their own objectives. The focus is on the interaction between the resource dynamics and its exploitation by different agents implementing various strategies. The consequences of their agricultural production practices and collective behavior for the risk of land degradation at the watershed level are assessed through a bottom-up aggregation of their effects from the small homogeneous piece of slope to the field, farm, and then village level.

The CORMAS ("common-pool resources and multi-agent systems," Bousquet et al. 1998; http://cormas.cirad.fr) simulation platform has been specifically tailored by Cirad for applying the MAS approach to INRM problems and has therefore been used to construct this model. Four types of agents were modeled:

- Situated agents having spatial references in the watershed (fields, etc.)
- Passive objects (crops, crop successions, farmers' practices, series of daily rainfall distribution)
- Communicating agents being able to receive messages: the village entity and three main types of farmers with contrasting objectives/strategies, amount of available resources, and degree of integration in the market economy
- Spatial entities located on the grid: an original characteristic of this MAS model is its built-in linkage with GIS maps of a watershed. This MAS-GIS link allows the model to handle dynamically two complementary spatial entities: small intrafield homogeneous units with regular slopes (they are used by the model to assess the effects of farmers' practices on the risk of soil erosion

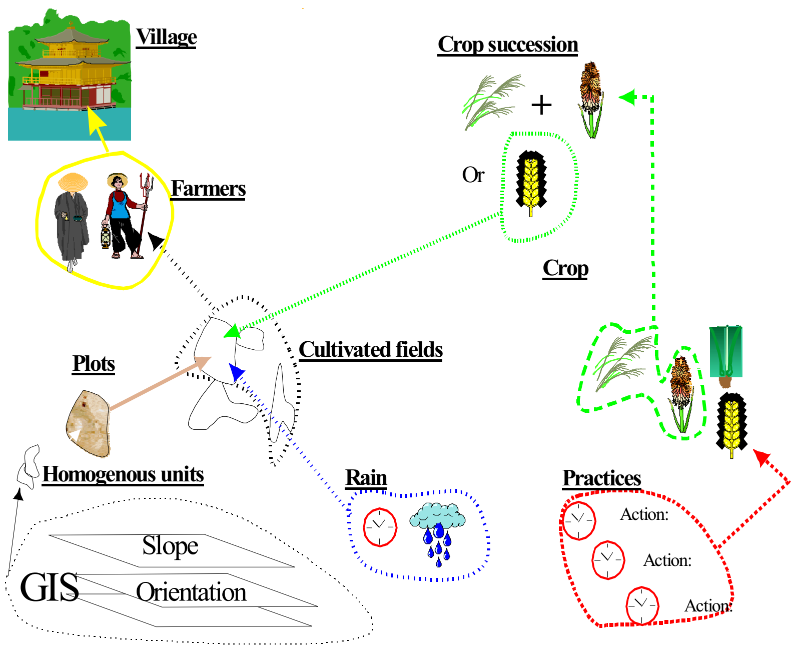

***Fig. 3.* General structure and entities of a multi-agent model for integrated watershed management in Chiang Rai Province, Upper Northern Thailand**

according to various rainfall distributions) and whole farmers' fields (used by the model to manage crop population dynamics and farmers' practices)

The model allocates various types of crops among the fields at the whole-farm level depending on the farmers' strategy and related choice of a combination of crops. Over time and as observed during field surveys, depending on the farmer's age and the economic results of cash-cropping activities, a given household can evolve into another farm type following a different strategy.

FLOW OF INFORMATION DURING THE SIMULATION

At the initialization stage, the model reads files to create the spatial units (small homogeneous units and whole fields), passive objects, and social entities (farmer types, the village). Afterward, it allocates fields to different farmers according to their category and numbers in each category. Then, for each field, an erosion index registering the severity and the frequency of erosion damage is initialized and set to nil. Next, farmers are asked to allocate their combinations of crops to their different fields according to their respective strategies. The village "decides" the start of the cropping year and "sends" the farmers to their fields. As soon as the wet season begins, if a potentially damaging rain event occurs (daily intensity > 10 mm), the soil coverage and slope conditions of each homogeneous unit in each field are checked. If the model finds that soil erosion occurred following this rain event, it gives a level of severity of the damage and updates the erosion index for this field. This procedure repeats itself until the end of the wet season.

OUTPUTS AND INDICATORS

At the end of a simulation, the model displays the spatial distribution of an index corresponding to the severity of soil erosion (fig. 4). This allows comparisons among various crop allocations and distributions of farmers among household types according to their effects on the risk of land degradation across climatic years. This indicator can also be used to assess the environmental effects of a given land-use scenario discussed and proposed by stakeholders. Apart from this environmental indicator, graphs can also show the changes over time in the social distribution of household types. This kind of socioeconomic indicator can be useful for answering the question "Who benefits?" when assessing a given land-use scenario defined with stakeholders.

MODEL VALIDATION: KEY ROLE OF "EXTERNAL" VALIDATION WITH STAKEHOLDERS

We do not aim at using MAS models to predict changes or to better control the simulated system. We choose to focus on understanding interactions between its different components and using such models in communication and negotiation support approaches. A two-step approach is proposed to validate this kind of model, especially to assess the coherence between the simulated processes and the actual ones represented by these simulations in a dynamic way. Following expert assessments of the results of simulations, further improvements and validation of the model will be carried out with its potential users, that is, the local stakeholders (Bousquet et al. 2001). An internal and more formal validation of the model itself also needs to be done to check the coherence of its coded rules with the model objectives. A statistical validation can always be added if suitable data sets are available. But, in our approach, it is essential that the model be found acceptable by the stakeholders so that it can be used in facilitating exchanges among them. We need to verify that, in the eyes of its potential users, the model is transparent enough, and that its key hypotheses can be considered as representative. Therefore, procedures for validation to be put in place must make the contents of the model explicit, and users must be able to verify the coherence between the observation and the simulation of dynamic events.

To do so, the MAS model is simplified and "translated" into the format of a role-playing game to be used with stakeholders. To limit the "black-box" effect when using

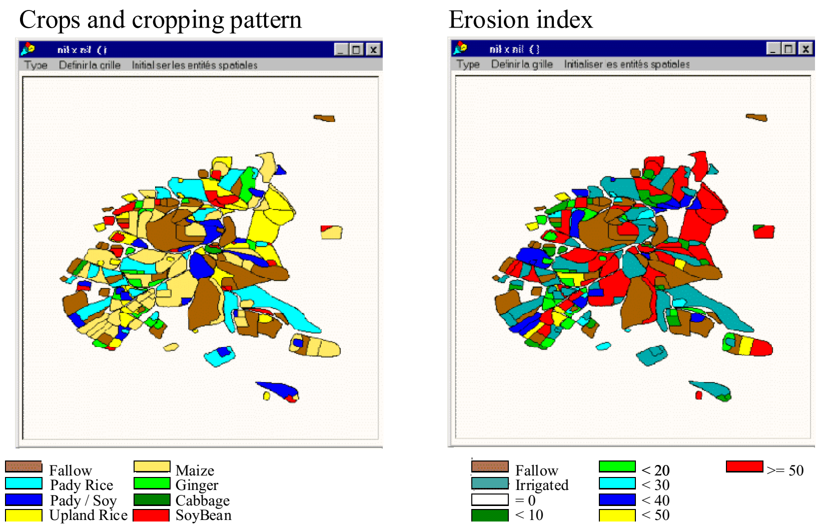

Fig. 4. **Simulated distribution of a soil erosion index for a given allocation of farmers' crops in the Mae Salaep Watershed, Mae Fah Luang District, Chiang Rai Province, Upper Northern Thailand.**

computer models, such a game helps local actors to familiarize themselves with the way the associated MAS model is working (Barreteau et al. 2001). We anticipate that this step will produce new knowledge on actors' strategies and decision-making processes. In return, this will lead to improvements in the original MAS-GIS model, while increasing its credibility and legitimacy. Because the role-playing game has a dual role (validation of the proposed representation of the system and production of new knowledge to improve it), a back-and-forth process between this interactive tool and the MAS model is an original feature of the companion modeling approach. Practically, the linkages between these tools can vary depending on circumstances, but the common aim is to generate a representation of the complex system under study, which is shared among all the concerned players.

THE "MAE SALAEP" ROLE-PLAYING GAME LINKED TO THE MAS MODEL

When used alone, role-playing games are reported to be of limited use for collective management of the land because they are difficult to set up and are time-consuming, while analyzing their results is usually difficult. By linking a role-playing game to a MAS model, we aim at removing these obstacles, while training stakeholders to use more powerful computer models in a "learning-by-simulating" way. In this section, we describe briefly the features of the role game to be used with stakeholders to enrich and validate the MAS model with them because they are the potential users of this kind of discussion/negotiation support tool.

Principles of the Mae Salaep Role Game

When conceiving this game, researchers have selected several key entities and interactions of the MAS model to be used in its construction. The various roles to be played in the game are based on the rules included in the MAS model. This way, the role-playing game can be considered as a simplified version of the more extensive computer model. Simplifications were made regarding the heterogeneity of the landscape, the time step, and the number of rules to be retained. The game leaves the definition of most of the social rules regarding land management to the participants themselves. This is because, beyond the different farm-level strategies already identified during previous on-farm surveys, the researcher-facilitator team is particularly interested in studying how collective arrangements among the players are emerging.

A participant in the game is going to play the individual role of a farmer managing several fields in a steep-land watershed of northern Thailand. Like him, other players of the same village will also manage their own fields in the same watershed. One player's objective is to manage his fields according to the roles and farming strategies described on the playing cards that he received at the beginning of the game. Three different types of farmers (A, B, and C) play together. They manage a different amount of resources (from one to five fields, initial amount of cash available, etc.) and adopt different combinations of crops and other activities according to their respective farming strategies. These farming strategies, the amount of resources available, and the subsequent orientation of their farming systems are specified on the "farm-type" playing cards distributed to the players.

The role-playing board is a 3D block model representing a simplified highland watershed with slopes of varying angles (four kinds of slopes corresponding to differing categories of slope angles are painted on the 3D block model). The steeper the slope, the more susceptible to soil and water degradation will be a field. During the gaming session, the watershed will be managed collectively by the players. Interactions among them are made of discussions, and exchanges of cash or fields or both.

Successive Steps of the Game

The game is played along successive crop years and each one is made up of several successive steps as follows:

1. Presentation of the general game rules (first crop year only).
2. Allocation of the different roles and farming strategies to the players by the facilitators (first crop year only).
3. Allocation of fields to the players according to their respective roles/strategies (first crop year only): each player draws a card to know how many fields he gets and their locations on the different kinds of slopes. As soon as a card is drawn, the corresponding fields are delimited (using bands of white paper and scotch tape) onto the 3D block diagram.
4. Credit allocation to the players: the village committee allocating credit to farmers is played by one of the players. In parallel, any player can try to get seasonal credit from any other player under their own conditions.
5. Players allocate their different crops to their fields according to their respective roles or strategies: at the beginning of the crop year, the price level of vegetable cash crops during the "previous" year is announced to the players: high, medium, or low prices. Players allocate their different crops to their fields using colored "Post It" stickers as symbols of different possible crops. Four players come to the board at each time and are assisted by four facilitators. The crop or fallow allocation to the different fields is recorded (video shooting, photographs of the playing board, collection of the Post It stickers labeled with farm or field or step numbers at the end of each crop year). Beyond the players' actions,

special attention is also given to significant attitudes and discussions or negotiations occurring among them.

6. The moderator announces the climatic conditions for the current rainy season: very wet (high soil erosion), wet, or dry (little soil erosion). According to the type of rainy season, the field location, its size, and the crop grown, a level of land degradation is assigned to each field during the current crop year and is expressed by a specific card.
7. Settling players' accounts at the end of the crop year: data are entered in an Excel spreadsheet to calculate gross product, family consumption, and the net income for each player. For each of his fields, each player pays the cost of the inputs according to the crop he selected and their allocation to its different fields. This cost is then deducted from the gross product and the player receives an amount of cash corresponding to the net margin achieved in each field under the given price conditions. If a player cannot reimburse his debts, the player either:

a) Becomes a wage earner and his family can grow only self-subsistence crops during the next two cropping years or
b) Sells one or more field(s) to another player willing to buy land. If he had only one field, then he stops playing; if he still retains one or more field(s) after the land sale, he continues to farm during the next crop year.

8. Initialization of the next crop year, and so on.

Players do well or badly during the game depending on their strategies and decisions, and on how vulnerable they are to (facilitator-decided) "chance" factors such as very strong rainy events or sudden drops in cash crop prices.

Preparation of the Room for a Gaming Session

The selection of the place where to hold the gaming sessions could have its importance. The location should not introduce any bias into the game. Wherever possible, a "neutral ground" is selected that favors the process of decentralized NRM.

The 3D block model of the watershed is set up on a large table in the middle of a large room. All the players sit in a circle around it, discussing and exchanging services and information while waiting for their turn to play. Separate desks are installed at different locations in the room: the "credit" desk to be visited by players looking for credit and the "market" desk where players come to clear their financial transactions at the end of each crop year. Another desk is used by the game moderator and the facilitator-researcher team (where results of the game are entered on spreadsheets, etc.). A white board is also available in the room as well as a bulletin board on which announcements for the current crop year are posted (climatic conditions, price of key crops, etc.).

The Participants

Enough players are needed to create a suitable level of complexity of the processes at work in the game, but their number is usually limited by the difficulty of managing a game with too many participants. In this case study, around 12 players, each one playing individually, represent a diversity of concerned stakeholders:

1. Three different categories of farmers: 3 type A, 6 type B, and 3 type C
2. One village trader, also a type C farmer
3. One player also represents the village committee allocating credit to farmers

Initially, only local stakeholders at the village level who are represented in the model are invited to play. Later on, more heterogeneity among the status of the participants could be added, especially if we decide to move on from a first step of mainly validation of the model to a second one dominated by scenario planning and assessment. In this second step, local resource managers and members of various development organizations can join the participatory modeling sessions.

Members of the facilitating team (6–8 persons) assist the players: one moderates the game, several help the participants at the game board, and others record the game and compute its results.

Time Frame and Succession of Gaming Sessions

We assume that a three-hour-long role-playing session is needed to explain the rules of the game and then to play a minimum of two successive crop years. This is usually the time needed to observe the emergence of some elements of coordination and negotiation. In a first morning session, the team of facilitators selects the key knowledge and features of the system to be used in the game on the basis of what they learned from previous fieldwork about the structure, behavior of actors, and land management rules of the system. Afterward, through usually lively discussions over lunch among the players and between them and the facilitating team, it is possible to play another version of the game, taking into account the comments and suggestions made by the participants. This time the facilitators let the players decide about the modification of some rules or the introduction of new ones to include new knowledge and representations of the system in the game. In this way, knowledge is shared collectively and dynamically. Beyond explicit features and management rules of the managed system, some more implicit ones can appear and be added to the game to enrich it if the players want to do so. For this to happen, it is important (at least initially) to call participants who are knowledgeable about the system, have a social status similar to the role they have to play, and are able to think about the relationship between the features and rules of the game and their actual on-farm circumstances.

Using MAS Models and Role-Playing Games with Stakeholders

The companion modeling approach is used to stimulate communication among stakeholders and a collective production of knowledge on the system under study. We think that this participatory modeling approach increases the actors' awareness of the diversity of points of view in the local community to be taken into consideration. In a recent experiment, a farmer-player even said that realizing this was the main output from the role-playing–simulating process.

As soon as stakeholders become familiar with the rules and the outputs of the role-playing game, an improved version of the MAS model incorporating the shared representation of the system can be used with them. Their knowledge of the structure and functioning rules of the model allows them to follow the simulations and to discuss their results. If they are satisfied by the model outputs, they can use this tool to explore the effects of various scenarios of land-use changes on both the natural environment and the socioeconomic status of the local farming community.

This on-farm modeling and simulation methodology, which is still being tested at various locations, usually follows four steps taking place over a five-day period:

- Day 1: preparation of the gaming session and selection of participants.
- Day 2: role playing (morning and afternoon sessions).
- Day 3–4: individual interviews with participants and programming of the revised MAS model (in parallel). These individual interviews build upon the actions of the players during the role play. Through a comparison with the real situation, the surveyors investigate the players' behavior and the various strategies developed during the role-playing game.
- Day 5: participatory modeling session based on scenario planning and computer simulations using the modified version of the MAS model. The extensive similarities between the role-playing game and the MAS model environment help participants to feel comfortable with the computerized simulations. Usually, the first one to be shown reproduces the role gaming session played on Tuesday. This presentation produces further discussion and the identification of different interesting scenarios to be simulated.

Participation of all key stakeholders should be maintained through the successive steps of the whole companion modeling process. This is not easy as such a process can usually last for quite a long time, and up to several years. But the gaming aspect of the role play helps create a friendly environment that facilitates communication among stakeholders, but also between them and the research team.

If the availability of the MAS model helps to conceive the role game, the analysis of the gaming sessions is still a rather difficult and time-consuming exercise. The comparison of the results of successive gaming sessions for different scenarios is not easy. Specific tools (such as analytical grids) need to be conceived and prepared to be able to do this more efficiently. But a lot of information and interesting points are made available during the collective discussions and individual interviews organized just after each gaming session.

The still-limited existing experience shows that the role game can play a key role in introducing the use of the computerized model and in making stakeholders understand what it is doing, why, and how. MAS modeling also allows the visualization of the results of simulations at various scales and from different points of view. Such displays of the results also facilitate their communication to local stakeholders. Better still, participants in the role-playing sessions are usually able to understand the relation between the model and reality. Having been through it, they know that the model is a considerable simplification. As a result, they can measure the importance of the results. As the aim is not to predict but to encourage and enrich discussion, simulations and role games serve to identify and formalize problems for discussion. The use of role-playing games could increase significantly the usefulness of such models in the eyes of the people involved in coordination and negotiation processes to improve land management.

If, in most situations, existing and relatively easily accessible information is available to get started when the practical problem to be examined is well-defined, such an approach to INRM research implies setting up functional interdisciplinary teams willing to adopt a collective learning attitude with stakeholders. To work on a given problem, in addition to NRM and social scientists, a modeler and computer scientist are required to transfer field knowledge into a MAS simulation tool.

As in participatory GIS, there is also a need here to ensure that the use of simulation tools with stakeholders does not limit the "flexibility" and adaptive capacity of the system, that this process of communication and negotiation-support does not violate privacy and confidentiality of information, or does not lead to increased surveillance among players, the marginalization of some of them, or the concentration of decision-making power in a few hands. This is why the spatial representation of the real system by the MAS model and the role game should not strictly follow its actual boundaries. This simplification of the spatial grid, for example, can facilitate the scaling-up of the lessons or findings found at a community level by making the tool adaptable for use in all similar communities. The function of a tool to stimulate interactive learning should be guaranteed.

CONCLUDING REMARKS

We found that the adopted MAS-GIS role-playing game-based companion modeling approach has the capacity and the flexibility to represent and integrate different kinds of (qualitative as well as quantitative) knowledge—across sources (indigenous and scientific ones) and at multiple levels of organization—to understand dynamically the functioning of complex agricultural systems such as a village watershed. The first key output of this participatory modeling approach is a shared and holistic type of representation of knowledge of a complex system seen as a set of dynamic and interconnected hierarchies. This common representation of the system can be used to support consensus building and collective agreement on its desirable state and agreed-upon concrete action to be taken to reach it. The common representation can be used as a coordination and negotiation support tool among stakeholders to assess scenarios of possible futures. Various options can be rapidly and interactively defined, simulated, and assessed with stakeholders to facilitate the emergence of socially and ecologically acceptable courses of action through improved interactions among them. On the basis of an understanding of natural and agronomic dynamics, this approach helps to identify acceptable rules for an improved regulation of collective uses of land resources by applying agreed-upon economic, legal, or institutional management tools. In this process, key intervention points are identified as well as suitable technological innovations and accompanying organizational and policy changes. This shared representation of the system can also be used to define appropriate indicators and monitoring procedures or information systems.

In this companion modeling approach, the complementary functions of MAS models and associated role-playing games are a key methodological feature for facilitating the communication of the results of agent-based simulations to stakeholders. When used in association in a process of conception or validation, the synergy among these tools is useful for empowering people to use them to tackle collective land management problems. When used as a mediation tool, the role-playing game can produce various and complex protocols of interactions that can later be tested by the MAS model to assess their specific effects on the system dynamics. The fact that fieldwork and modeling activities are seen as complementary and that they are closely linked in an iterative way is also remarkable. We think that companion modeling provides a workable way for researchers to closely articulate their field and modeling activities. This approach could also help close the "digital divide" and fill the current gap between more and more hi-tech modeling procedures and on-farm research and development. Thanks to the extensive flexibility of MAS modeling, the construction of simple generic models to move beyond the usual site-specificity of NRM research can also be achieved.

An important research activity in our future work plan will be the analysis of the use of this companion modeling approach and mediating tools for group decision support through improved communication, coordination, and negotiation when attempting to tackle INRM problems in different agricultural contexts. We think that as much importance should be given to the validation of the way this approach is being put to use as to the validation of the MAS modeling exercise itself. How to measure the effects of such facilitation processes will also be a key question to be answered in the future.

Where the general policy-making framework regarding the land is characterized by a decentralization of the local management of natural resources, we think that a multi-agent systems-based companion modeling approach is of great interest for improving the collective management of the land, particularly to facilitate dialogue, to mitigate conflicts, to build consensus, and to establish coordination mechanisms regarding multiple uses of the land by multiple stakeholders. It is also an interesting way to integrate knowledge from different sources, and to assess suitable innovations and desirable scenarios for the future.

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