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MIRANA: a socio-ecological model for assessing sustainability of community-based regulations

Sigrid Aubert[a,b], Jean-Pierre Müller[a], Julliard Ralihalizara[b]
[a]*CIRAD-GREEN, Campus International de Baillarguet, 34398 Montpellier cedex 5, France (sigrid.aubert@cirad.fr,jean-pierre.muller@cirad.fr)*
[b]*CIRAD-Forêt et biodiversité, B.P. 853, Antananarivo 101, Madagascar (julliard.rali@gmail.com)*

Abstract: The Malagasy local communities managing forest resources have difficulties in assessing the impacts of the management plans they decide upon. To help them, we have designed an integrated model with the ecological processes, the various regulations (zoning, quota, etc..) and the resulting inhabitants behavior in order to explore the impacts of scenarios. The model MIRANA has been designed using the MIMOSA framework in which one must design a conceptual model using ontologies, annotate the conceptual model with the necessary processes, and design a concrete model from which to generate the simulation model. In MIRANA, the conceptual model is made of the set of ontologies describing the actors of the system (households, communities, etc.), the objects they are acting on (lands, animal and vegetal species, etc.), the actions carried out by the actors on the objects (hunting, cultivation, etc.) and the regulations on the actions. The actors are provided with needs (food, money, etc.) or objectives (conservation, production, etc.) and planning mechanisms. The objects are provided with spontaneous processes (fertility dynamics, growth of biomass, etc.). This paper is focused on the representation and use of a multiplicity of normative structures for the regulation of the interactions with the environment.

***Keywords**:* sustainable development; forest management; governance; ontology; multi-agent system; institution; norm.

1. INTRODUCTION

In Madagascar, the management of forest resources is gradually transfered to the local communities according to the law 96-025 of September 30. 1996, called GELOSE. Its implementation order n° 2001-12 of February 14. 2001, called GCF, defines the conditions of implementation of contractualized management of the state forests. However, local communities are likely to have difficulties assessing the consequences of management plans they ought to implement and to enforce. In particular, forest restoration does not appear to be a worthy investment as shown by Baudoin [2008] and Bouvre [2008]. In order to highlight the possible interest of forest restoration for the local communities, we have developed a computer application allowing to simulate various scenarios of implementation of management plans. The application allows us to test various options for their conservation and their sustainable uses, to discuss the impact of the human activities on both the forest ecosystem and the sharing of the advantages from a sustainable use of forest resources on local development. Therefore, we are considering simultaneously the environmental, social and economic sustainability.

The aim of this paper is to present the MIRANA model we have designed as an answer to these requirements. The originality of this model is to account not only for the individual practices and the economic exchanges, but also for the regulations by a multiplicity of normative structures. In effect, most existing models only handles regulations through economic mechanisms (incentives and taxes) neglecting the effect of customary rules and their interactions with more formal (and multiple) regulations like zoning, quotas, permits and contracts. The realm of multi-agent systems (MAS) is schematically divided between

the cognitive agents directly interacting among themselves and the reactive agents indirectly interacting through the environment. The normative structures, or institutions, are usually devoted to cognitive agents and, therefore, regulate the interactions among the agents (e.g. Campos & al. [2008], Dignum [2004], Hübner & al. [2007]). The MIRANA model is dealing with resources management, hence with the regulations of the interactions with the environment. In this paper, we will describe how these regulations are represented in the field of legal anthropology and will propose an implementation for multi-agents systems.
After having presented and justified the methodology used for designing the model, we shall introduce the model in five sections: the conceptual model, the dynamics, the initial state, the indicators and a brief description of the model implementation. Finally before concluding, we shall present some preliminary results.

2. THE METHOD

As a general framework, we are using the Companion Modeling approach as described by Antona [2003]. It consists in coupling the scientists' knowledge production process with the stakeholders' decision process by building a shared understanding of the relevant system and its issues using modeling. The model building process goes through a cycle of hypotheses formulation, model building, validation and amendment with the stakeholders through role-playing games and/or scenario explorations. Farolfi & al. [*to be published*] formalized the model building process. This process is divided into the following steps: 1) the design of a conceptual model using ontologies (Müller [2007], Livet et al. [2010]) in order to formalize the discourse of both the stakeholders and the implied scientists. It produces a set of concepts or categories with attributes, structured by taxonomic and semantic relationships, which are used to describe the system under study, 2) the description of the processes associated to the categories endowed with dynamics like the species, the actors and other biophysical or social items, 3) the description of the initial states and parameters describing as many concrete instances or models of the system under study, 4) the description of the observables or indicators one wants to collect on the simulations in order to answer the relevant questions we have about the system, 5) and finally, the implementation of the above-mentioned descriptions with the technical choices including for the initial states (data bases, files, etc.) and representations of the indicators (data bases, plots, graphs, etc.).
These steps correspond roughly to the ODD protocol proposed by Grimm et al. [2006] but: 1) the distinction between the conceptual descriptions (using the UML class diagrams as graphical representations (Bommel & Müller [2007])) and the implementation, 2) the explicit description of the observables related to the purpose of the model, 3) the mapping of the various categories of the ontologies to sets of process descriptions, 4) the support of the design process by a modeling platform called Mimosa (Müller [2004]) with a well defined operational semantics (Müller [2009]). We shall use the above-described methodology in the following to describe the resulting model.

3. THE MIRANA MODEL

3.1 The conceptual model

The conceptual model is made of the set of ontologies describing the actors of the system (households, community, etc.), the objects they are acting on (lands, animal and vegetal species, etc.), the actions carried out by the actors on the objects (hunting, cultivating, selling, etc.) and the regulations.
In law anthropology, each actor is submitted to a number of regulatory systems. The regulatory systems that apply to an actor depend both on its memberships and its geographical situation. An actor is member of a large number of formal (associations, companies, countries, etc.) and informal (family, fan groups, etc.) institutions. Each institution defines the functioning of a group of people, including its ontologies and norms (Ostrom [1990]). An actor is also situated geographically within a set of areas that can be embedded in one another (village, region, country, etc.) or intersecting (classified forest, cultivable areas). Here, we only consider areas on which regulations apply. It means that formal and informal institutions also control these areas. The actors are submitted to the regulations of these institutions just by being situated in the controlled area. Therefore, an

actor is permanently submitted to numerous formal and informal regulations, which can possibly contradict each other. In our model, the resulting behavior shall depend on the capacity of the household to satisfy his needs with all or only part of its patrimony. Therefore, breaking regulations is possible.

There are two kinds of actors: the individual actors and the collective actors (Figure 1). In our case, the individual actors are the households (juridically, they should be the individual persons). One must distinguish the institutions and the collective actors. An institution reifies regulations among members (called network institutions) or upon territories (called territorialized institutions). When an institution is formal, it exists juridically as an actor. Therefore, it is itself submitted to regulations (a commune is submitted to regulations of the province as a formal institution). In Figure 1, the VOI (the local community), the park administration and the commune are actors endowed with objectives (protection, etc.). The lineage is an institution but not an actor as far as no (even traditional) authority has been identified.

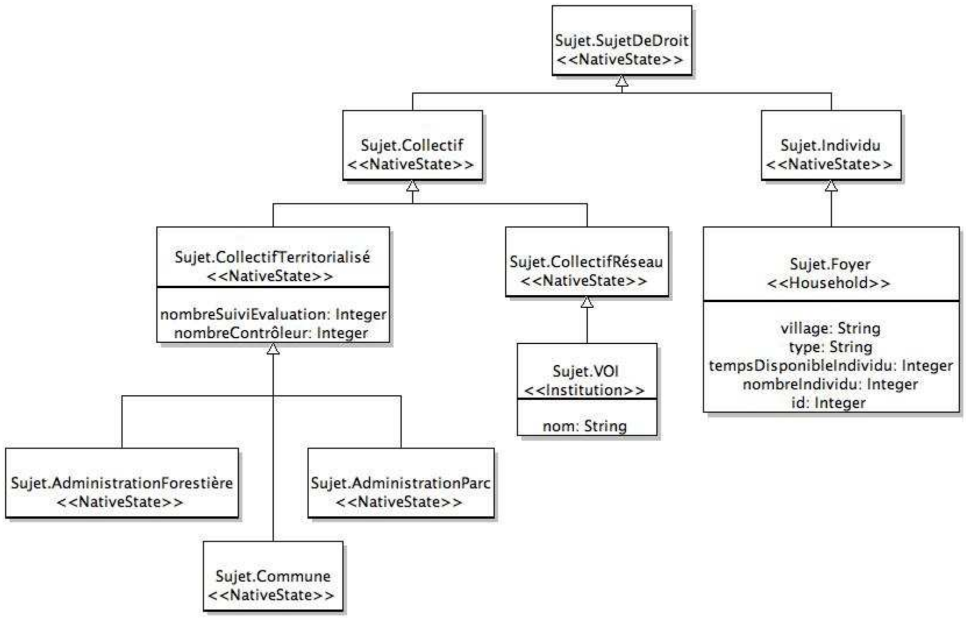

Figure 1. The actors implied in the management transfer (in french).

Regulations within an institution are reified by legal acts. In law anthropology, a legal act can be written or not. Each institution defines explicitly or implicitly what constitutes a legal act for it (not only the State). A legal act is composed of a set of norms describing the expected behavior among the actors and/or with respect to objects (species, lands, etc.). These broad definitions entail any social construct aiming at regulating the interactions among people and with the environment (including its biophysical and immaterial aspects). Given our application to natural resources management, we are mainly concerned with norms concerning the usage modalities of the resources. In our case, a norm is a relation between a subject and an object. More formally, a norm is a triple <RS,RO,DR> where RS is the role endorsed by the subject (owner, seller, etc..), RO the role attributed to the object (product, good, etc.) and DR a set of permissions, prohibitions and/or obligations on the actions the subject could perform on the object. Regarding the resources, the actions are classified in four categories: usage (for the subject's needs), exploitation (for selling), exclusion (to prevent use by a third party), and transfer. The land is considered separately using the installing actions like building a house, growing crops, etc.

The legal acts we are considering are 1) the zonings which define the rights (or prohibition) of usage and/or exploitation and/or installing on given areas, 2) permits of usage, 3) permits (or contracts) of exploitation. The institutions we are considering are the lineage, the community, the commune and the forest administration. The lineage provides usage rights for the members of the lineage upon portions of the forest. The community is the institution to which the management is transfered. The community has to define the zoning as well as the permit policy. The commune and the forest administration superimpose additional zonings and quotas.

In multi-agent systems, an institution is defined as a set of roles together with the specification of the expected behavior for each role (e.g. Sierra & al. [2004]). Being mainly devoted to cognitive agents interacting among them, the expected behavior is represented by obligations, permissions and prohibition on speech acts (Campos & al. [2008]), goals (Dignum [2004]) or missions (Hübner & al. [2007]). Using the norms for regulating the interactions with environment is a natural extension when dealing with resources management. These norms also define which objects count as a good, a product, etc. Therefore the norms also define the categories (or roles) in which the objects can be classified (Pottage & Murdy [2004]). With the notion of legal act, we also provide a representation unit, which is at the same time coarser than a norm (being a set of norms) and finer than an institution by defining the roles the actors and objects can play for each interaction context within an institution.

Although most of the activities are related to self-subsistence, introducing markets with exogenous prices for wood productions, rice and meat also provides an economic account. At the administrative level, the source of income is essentially the taxes on the markets and the fines; the expenses are the compensations for sustainable use and forest restoration.

3.2 The dynamics

Aiming at genericity, we have defined basic structures of operations in which the dynamics can be expressed. The basic structures are *simple entities* SE_i organized into *spaces* $S = (SE_i, N, M, V)$ where SE_i are the simple entities, N is a set of names or coordinates, M is a mapping from N into SE_i attributing a unique name for each entity, and V is a neighborhood relation. A space can represent a physical space in which the names are coordinates and V is adjacency, or a social space where V represents the social network, or even an unstructured population when V is empty. Any entity can be situated onto other entities in other spaces. It is represented by a set of functions called *situations* from a space into another. The basic operations on the spaces consist in creating or removing entities from the spaces (with their associated name) as well as changing the neighborhood relationship. The later allows the space structure to dynamically change. The basic operations on the situations consist in adding or removing a mapping from an entity to another and in changing the mapping. The later operation describes movements of entities within a given space. It may or may not comply with the neighborhood relation of the target space.

To each entity is associated a set of stocks. A *stock* is a *resource* and either a quantity (aggregated account) or a set of resource items (individual account). The operations on the stocks consist in creating and removing as well as increasing and decreasing the stock (including by adding and removing resource items), in transforming parts of stocks into other stocks, in moving a part of a stock of an entity into another entity. The later is only possible if the entities are situated on one another or neighbors. With these operations we can describe stock variations, transformations and flows.

Based on these basic structures, we define two kinds of dynamics:

- The biophysical dynamics as spontaneous evolution of stocks. As examples, we have the population growth of the species and the evolution of the fertility. Currently, we do not consider stock flows as, for example, the migration of species when the habitat changes. The dynamics are represented as equations of time and the corresponding operations executed at determined time steps.
- The decision process of the agents (representing the households and the collective actors like the local community, the commune, etc.) is described below in more details.

From a dynamical point of view, the institutions influence the actors' behavior as well as the actors use the institutions for their own sake. Accordingly, both the holistic and individual perspectives have to be taken into account.

From a holistic perspective, each institution defines how the regulations are enforced. This enforcement is implemented by a police function and a judiciary function. The role of the police function is to notice the illegality of the actions of the actors submitted to the regulations. This role can be played by the members themselves (social control) or delegated to some dedicated actors (in which case, the institution must be an actor). The role of the judiciary function is to punish the actors having performed illegal actions. Each institution defines how the decisions and punishments are managed (traditional chief, judge, etc.). In multi-agent systems, Vazquez-Salceda & al. [2004] proposes such a mechanism for electronic institutions.

From an individual perspective, each actor defines how the regulations that apply to him are taken into account. Each actor knows of which institution he is member. It may know or not which institutional regulations apply to him just by acting at a given place. Therefore, its decisions will depend on its needs and objectives and their relative importance as well as the numerous institutions he is part of and their relative importance. The importance of an institution is a matter of social proximity, efficiency of the police function, reward or punishment for performing something. In multi-agent systems, Lopez & al. [2002] proposes agent architecture for doing so with various strategies from obedient to rebellious. We propose a simplified account but with an institution ranking.
More concretely, a household plans its actions depending on its needs. It searches for a place where the action is allowed regarding the institutions it is submitted to. If none can be found, some norms are released in priority order unless the household is legalist. Then the usage or exploitation permits are requested to the regulatory institutions. If not granted, the action becomes illegal or is not performed.
The regulatory institutions grant usage and exploitation permits based on quotas and policies. Additionally, exploitation, conservation and police activities are contracted with the households.

3.3 The initial states

Excel tables define the various populations with their characteristics and situations. Each species is described by its expected density on the various habitats. The typology of households is described and situated on the various villages. These descriptions are used to generate a random repartition of the populations in the habitats and the villages. Vector maps define the geometry of the habitats, villages, roads, rivers and zonings.
The dynamics of the species are parameterized as well (growth rate). The decision dynamics of the households is given as a prioritized set of needs to fulfill (see Table 1) by household type. Additionally, the initial memberships of the household are given with the need they contribute to and a priority order of execution when satisfying the same need (for example, for the need in cereals, the shallows are favorite and then slash and burn, and finally by buying it on the market).

Type	Priorite	Produit	Unite	Quantite
Marais	6	Finance	ariary	300000
Marais	4	Kitay	kg	100
Marais	3	PlanteMedicinale	kg	10
Marais	5	Plateau	int	10
Marais	2	Poisson	kg	0
Marais	1	Riz	kg	0
Marais	5	Traverse	int	0
Marais	2	Viande	kg	0
Foret	6	Finance	ariary	300000
Foret	4	Kitay	kg	200
Foret	3	PlanteMedicinale	kg	10
Foret	5	Plateau	int	10
Foret	2	Poisson	kg	10
Foret	1	Riz	kg	300
Foret	5	Traverse	int	18
Foret	2	Viande	kg	50
NonAutochtone	6	Finance	ariary	0
NonAutochtone	4	Kitay	kg	0
NonAutochtone	3	PlanteMedicinale	kg	0
NonAutochtone	5	Plateau	int	10
NonAutochtone	2	Poisson	kg	0
NonAutochtone	1	Riz	kg	0
NonAutochtone	5	Traverse	int	9
NonAutochtone	2	Viande	kg	0

Table 1. The table of the needs by household type with the priorities (in french).

Finally, the norms are defined by zoning maps, the membership of the households to customary and administrative communities, as well as attribution of roles to the various species (for example, for subsistence and/or selling, etc.).

3.4 The indicators

The aim of the model being to assess the sustainability of the management plan in ecological, social and economical terms, the indicators are directly related to the sustainability issue. Accordingly, they are divided into three groups: 1) the conservation indicators regarding the evolution of the habitats (surfaces and fragmentation) and of the species populations, 2) the management indicators like the percentage of actual and reported regulation violations (quotas, zoning, etc.), the regeneration actions, the compensations for conservation, 3) the production indicators as the average income, need satisfaction rates, average fertility evolution, etc. For the time being, only the surfaces of the habitats, surface of cleared land, soil fertility and rice need satisfaction rate are computed.

3.5 The implementation

In this paper, we shall not describe in detail the implementation. The global architecture is described in Figure 2. The initial state and parameter values as described by a number of maps (habitats, zoning, villages, roads, etc.) and an excel file as described in section 3.3 are used to generate data base tables using a PostGreSQL server extended with PostGIS for the spatial data.

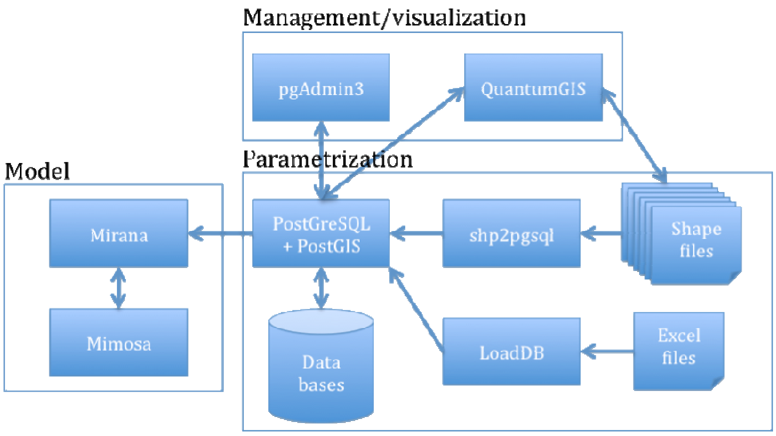

Figure 2. The global architecture of the implementation.

The MIRANA model itself includes the conceptual model (section 3.1), the processes (section 3.2) written directly in the Java programming language for efficiency, and the concrete model (section 3.3) describing a particular place (in our example, the community forest of Antontona). When launching the concrete model using Mimosa, it reads the initial state and parameters from the databases, generates a DEVS simulation model (Zeigler [2000]) and run it producing the desired indicators and visualizations as outputs. The indicators are also recorded in the database for further handling.
For sensitivity analysis, the whole system is launched in batch mode (without the user interface) from MatLab that incrementally changes the various parameter values in the database and records the resulting outputs from the database.

4. PRELIMINARY RESULTS

We obtained only some preliminary results given that only rice growing was implemented in order to fulfill the need in cereals. However, it was possible to assess the impact of the population on the degradation of land for livelihood only. Figure 3 illustrates the impact on the shallows of 26 households (70 people) of which the half are complying with zoning constraints.

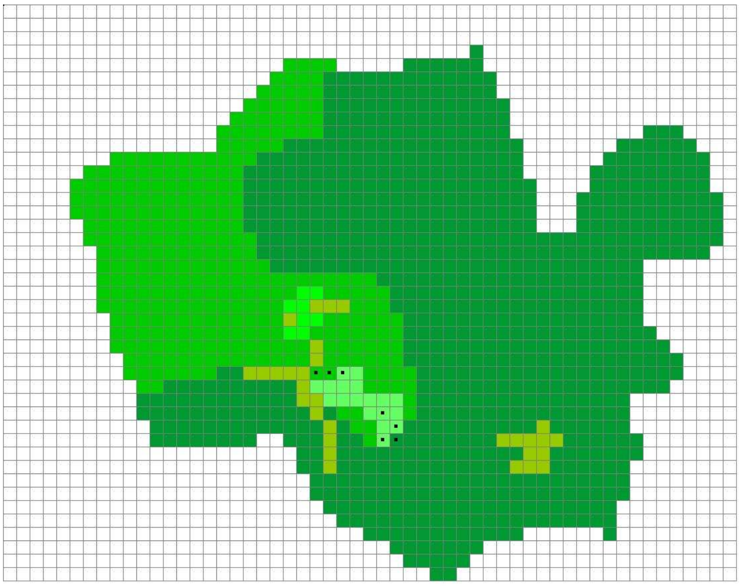

Figure 3. The map of habitats from dark to light: primary forest, secondary forest, fallow, culture (yellowish), and degraded land.

We already built the indicator for need satisfaction rate but we do not have the results yet. Further steps include taking into account the loss of fertility (already computed) and the resulting disuse of plots, the side effect of the grid size (to be corrected later), and, of course, the addition of other activities (and competition among these on available labor force).

5. CONCLUSION AND PERSPECTIVES

We have presented the MIRANA model with a first attempt, as far as we know, to incorporate norms into socio-ecosystem simulations. We proposed a generalized representation of norms as relations attributing roles to assignees and objects together with rights and prohibitions. These norms are encapsulated into legal acts. From an analysis of the various norm structures from customary to administrative ones, we obtained a set of roles for the actors and the objects. These roles were used to describe the biophysical and social dynamics relevant to the question asked: what is the impact of the community level regulations on the actual ecological, economical and social sustainability of the local community and its territory? For expressing these dynamics, we proposed a simple underlying structure of operations on spaces made of entities possibly situated in other spaces and endowed with stocks. We argue that all the dynamics we are describing shall result in the execution of the proposed operations. Finally, we showed some preliminary simulation results.

Much work remains to be done. First of all, we shall extend the set of roles currently implemented to assess the complex interactions among a multiplicity of needs. The dynamics at the level of the local community with its objectives in terms of conservation and production and the related financing mechanism, is not yet implemented. Of course, further sensitivity analysis shall follow. Finally, we still have to use this model to discuss with the local communities themselves.

In a more distant future, we shall try to use this model with different maps and species to apply it to completely different situations, assessing this way, its possible genericity as a model of renewable resources management.

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