Integrated assessment modelling of environmental impacts of land use policy in West-Africa: A conceptual model

Mahamadou Belem [1] — Melio Sáenz [2] — Mehdi Saqalli [3]— Nicolas Maestripieri [3]

1. West African Science Service Center on Climate Change and Adapted Land Use, 6 P.O Box 9507 Ouagadougou 06, Burkina Faso.
mahamadou.belem@gmail.com
2. Centre Latino-Américain de Calcul Scientifique et d'Informatique Industrielle
msaenz47@gmail.com
3. Université Toulouse 2 Jean Jaurès,GEODE Géographie de l'Environnement,
mehdi.saqalli@univ-tlse2.fr

RÉSUMÉ. *Cette communication traite des éléments à considérer pour la mise en place d'un modèle informatique spatialisé formalisant l'impact prospectiviste de politiques publiques d'usage des terres en terme environnemental. Cet objectif, appliqué à l'Afrique de l'Ouest, nécessite d'intégrer des spécificités de cette sous-région, en particulier d'une part la difficulté de créer un corpus de données rendant possible cette modélisation et d'autre part l'intégration de la grande variabilité du milieu biophysique et des statuts fonciers.*

ABSTRACT. *This communication discusses considerations for the establishment of a spatialized computer model formalizing a prospective of the environmental impacts of public policies regarding land uses. This objective, once applied in West Africa, needs to face several challenges specific to the sub-region: on the one hand, the difficulty of creating a set of data strong enough for enabling the modelling process and on the other hand, the integration of the high variability of its environment, both biophysical (rainfall first) and socially (land tenures first).*

MOTS-CLÉS : *modélisation, modèle conceptuel spatialisé, Afrique de l'Ouest, usages des terres, politiques publiques sur le foncier.*

KEYWORDS: *modelling, spatialized conceptual model, West Africa, land uses, land public policies.*

1. Introduction

1.1. Context and issues

In West-African countries, as in many developing countries, the successful formulation and implementation of land use policies are often hampered by the fact that whatever the issue, we usually do not have enough knowledge about their impacts on global scenarios, especially those related with sustainable development, because of:

- The non-availability of good data of the present-time situation, from the biophysical dynamics occurring on the present time to the cadastre itself, but also the weight of uses acting on any piece of land, let aside the temporal accuracy of these data;
- The absence of scientifically-based but locally adapted tools to process this information: for instance, assessing the use of a piece of land without integrating the multi-ownership and right of use occurring in West Africa on a global scale implies many oversimplification to force the west situation to fit with western standards;

In this paper, we propose modelling tools in this context to process this data in order to obtain useful information for planning and making decisions in terms of sustainability, taking account that both data in quality and quantity are considered as enough.

1.2. Which principles for modelling environmental impacts of land use policy?

Building tools needs a clear understanding of reality. It means scholars tending to build such tools need to search the reference system structure and its functionality.

Our departure point is defined by three macro-systems: Nature, Life and Society. Each of them contributes with elements to the structure and from their properties they are defined the inter-relations or it is possible to identify those that are not specified.

The second step looks for describing the state of the system, operation which is made with help of a subset of variables identified in the system and that constitute our useful set of variables called "relevant variables". At this level we must know limitations and restrictions with which we will deal for our purposes. These limitations and restrictions arise from the simplification of reality, that is, from the model formulation.

To be able to consider the various facets of a problem at hand, modeling has proven to be an appropriate tool to provide and combine the necessary information (Herrmann*et al.* 2011). Models can help blending knowledge and perspectives from different points of view (Belem *et al.* 2011). Models provide an effective framework to formulate, simulate different scenarios and to underline the potential impacts of decisions (Saqalli *et al.* 2011). Models allow handling the dynamics of a complex system at different scales of description and the interactions that exist between the different scales of description.

The objective of this paper is to propose a conceptual framework for the multi-scale integrated representation and modeling of land use policy impacts in West-Africa. Specifically, our main aim is to propose a common and shared representation of land use and land management systems in West-Africa for assessing the concurrent impacts of different land use and land management practices on major ecosystem services and disservices, such as carbon and nitrogen storage, water quality and availability, soil degradation, biodiversity losses, and greenhouse gas emission. We consider also social aspects such as poverty reduction and food security, and economic benefits such as income generation.

Practically, many stakeholders are concerned by the land use and land management issues. These stakeholders have not the same understanding and the same point of view on the real objects of the system. Their points of view can be complementary or opposite. However, it is necessary to integrate these various points of view for a better understanding of the target problem. For that, we need a common framework to provide a common representation of the target system but also for knowledge integration from different sources. We need to consider that three fluxes occur in systems: Matter, Energy and Information. On their basis, it is possible to establish relationships among the elements and with the environment.

2. Research approach

The research approach is based on multi-dimensional and multi-level approaches. The objective is to target the land use dynamics at different scales while taking into account the social, economic, bio physical and policy dimensions. In order to consider the stakeholders involvement, the conceptual model is based on the general framework for analyzing sustainability of socio-ecological systems developed by Ostrom (2009). Stringer *et al,* (2013) argued that the involvement of multiple stakeholders, with highly differing objectives and perspectives, illustrates the need to pay attention to the multilevel, nested, and networked nature of Human-Environment systems. In addition, multi-scale approach is essential to allow inter-connections between regions and scales to be identified on a more manageable landscape scale, as well as to enable integration of the outputs from large-scale analysis typical of climate, economic or land use change modeling and vulnerability analyses, with local-scale assessments of the drivers and impacts of degradation at a household, village and district level (Stringer *et al*, 2013)

We seek to provide a common framework for sharing the different representations of land use systems in West-Africa and for knowledge integration from different sources. The general framework for analyzing sustainability of socio-ecological system is based on the assumption that the socio-ecological system (SESs) are composed of multiple subsystems and internal variables within these subsystems at multiple levels. This formalization should concern various land use practices regarding agriculture, forestry, pastoralism, water management, etc. The objective is to assess the competing impacts of different land use practices and policy scenarios on environment (soil degradation, biodiversity loss, carbon & nitrogen storage, water quality and availability, CO2 emission, etc.), society (poverty reduction, food security, health, inequality, etc.) and economic benefits (crop yields, incomes, etc.). That will be achieved by accounting the interactions between social, economic and biophysical dimensions at field, farm, village and region scales (Figure 1).

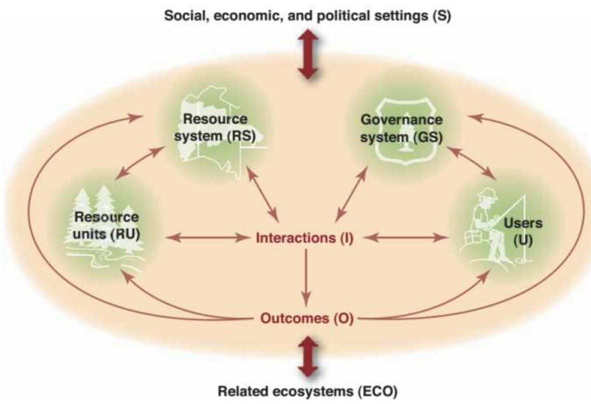


Figure 1: the general framework for analyzing sustainability of socio-ecological system (Ostrom 2009).

Using the conceptual model, a meta-model is developed for representing the land use and land management systems in West-Africa. Several specificities do occur in West Africa, comparing to other locations in the world:

- Climate, and more specifically rainfall, is not only varying along latitude, i.e. spatial discrimination. It varies according to seasons such as the majority of locations in the world. It also vary a lot in time and space between and within years: this high spatial and temporal intra-annual and inter-annual rainfall variability (Sangaré *et al,* 2001; Gérard et Buerkert, 2001) may double the rain volume for one site between two years and between sites distant of less than 500 m in the same year!

- The land tenure problem in West Africa is indeed extremely complex: there are a lot of different tenure statutes and their definitions are difficult to establish, particularly for villages in conflict (Le Bris et al., 1991; Lavigne-Delville, 1998). Moreover, such tenure systems do evolve quickly along time;

3. Results

3.1. The conceptual model

3.1.1. Resources system

We based our figures upon the UML representation symbolism (Unifed Modelling Language). The use of the Unified Modeling Language (UML) as the "official" mode of representation of modeling procedures is becoming widespread. Numerous research documents use this language in their communications with other researchers. However, this use has not spread outside of the model makers' community. We however plea for a better formalization and a stronger understanding within this community and between this last and scholars belonging to other sciences and we then stand on this procedure.

In this study, we are concerned by different land use sectors: the agriculture, water, forest and pasture. The objective is to assess the concurrent impacts of different land use sectors. As we consider the land use and land management systems as socio-ecosystem, we are interested in the interactions between the two ecological and sociological systems at different scales of representation. The ecological system in our conceptual model is represented by the soil, animal, crop, grassland, tree and water components, their own dynamics and interactions. They represent the majors resources used and impacted by the climate and land use and land management in West-Africa.

- The animal component concerns only the cattle, sheet and boat that have the most important impacts of land use and land management. The crop component represents a range of species. The tree component represents also a range of species.
- The social system represents the human societies, the economic activities, the social organization and the institutional context. Farmers are the main stakeholders concerned by this study. Farmers belong to different social-organizations on which depends in part of resources and the information access. In addition to farmers, stakeholders concern the public policy agent, local authorities, advisory services, farmers organizations, non-governmental organizations, research institution, projects , enterprises.

In conclusion, the governance system of land use and land management in our conceptual model is composed of farmers, Government Organization, Non-Government Organization, Farmers Organization, Enterprise,

3.1.2. Interactions

3.1.2.1. Multi-dimensional and multi-level interactions

The conceptual model takes account four level of description: plot, farm, local and regional scales. Specifically, we seek to analyze the feedbacks loops between these different scales and the governance system that exists at each scale (Table 1).

Table 1: Multi-level representation of land use and land management

Regional level	Local level	Farm level	Plot level
Land use planning	Social networks dynamics	Crop, livestock and tree management	Interactions between soil-plant-atmosphere
Technology diffusion	Collective land management (Forest, pasture and water management)	Fertilizers management, Manure production	Bio-chemical cycle: carbon, nitrogen, phosphorus, etc.
Regional market dynamics (cost of inputs, cost of labor, price of foods, etc.)	Resources exchanges	Labor management	Crop yields, biomass production
Climate dynamics (rainfall, temperature)	Technology diffusion	Off-farm activities managements	
	Local market	Innovation	
		Adaptation	
	Local Climate dynamics	Learning	
	Land use planning	Risk management	
	Local population growth	Gender implication	
	Social structural change (change in farmers typology)	Income generation	
	Spatial structural change (change in spatial pattern)		

3.1.2.1. The social interactions

In order to represent the interactions between the different stakeholders, three major interacting communication systems are defined. The communication system represents a network that defines the types of relationships between the stakeholders and their interactions. In our study, the communication system is composed by the social, the institutional and the market networks:

1. **The social network** describes the social relationships and interactions between farmers through different social groups (ethnic, family, neighbourhood). In the social network, the interactions concern exchange for seeds, labour, land, manure, etc. ;
2. The **institutional network** describes the relations and the interactions between organizations (Government Organisation, NGO, Farmer Organization, Enterprise, Research Institution, etc.). The institutions interact between them to coordinate their activities and use the institutional network to support the farmers' activities;
3. The **Market network:** It will include both price variations and connections, i.e. practical, social and legal restrictions to the free theoretical market (customs, family and social networks, impacts of market sizes and distances).

3.2. *Toward a generic and integrated meta-model for land use and management representation in West-Africa*

Based on the general conceptual framework defined, a generic and integrated meta-model is developed to define a common and shared representation of land use and land management in West-Africa (Figure 2). The meta-model is composed of different components of land use and land management system. That concerns the meteorology data, the land and land cover specification, the spatial organization of the targeted system. In addition, the meta-model defines the socio-economic characteristics of the households (Figure 3), the policies supports to households (Figure 4) and their activities (Figure 5). The meta-model integrates the land management practices and their socio-economic impacts. The land management concerns the crop, water, livestock and forest management. Finally, a biophysical component describes the soil and plant characteristics.

For example the household meta-model defines the typology of household from social, economic and policy point of view. From the social point of view, it defines the type of household characteristics: number, farm family size, farm size (ha), livestock size, external income, cropping system, number of external workers, the socio-professional networks. In addition, the meta-model describes the family composition: the groups age, the birth and death rates, labor provided by each group age, money need, female proportion in the group, migration rate of the group, etc. From the economic point of view, the meta-model describes the occupation of the households (farmers, off-farm work) and their activities (crop production, livestock production and forestry activity). From the policy point of view, the meta-model describes the different types on interventions (aid, credit, crop insurance, Off-Farm Wage labor, etc.) that household can beneficiate from the policy makers, project developers, etc.

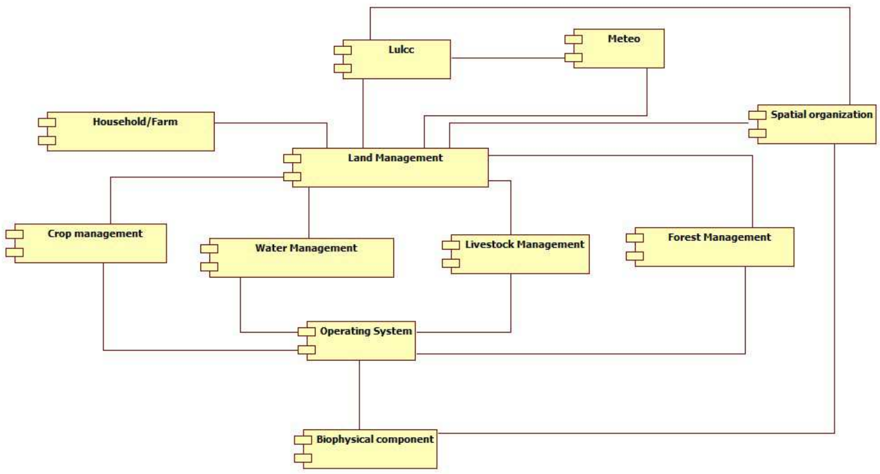
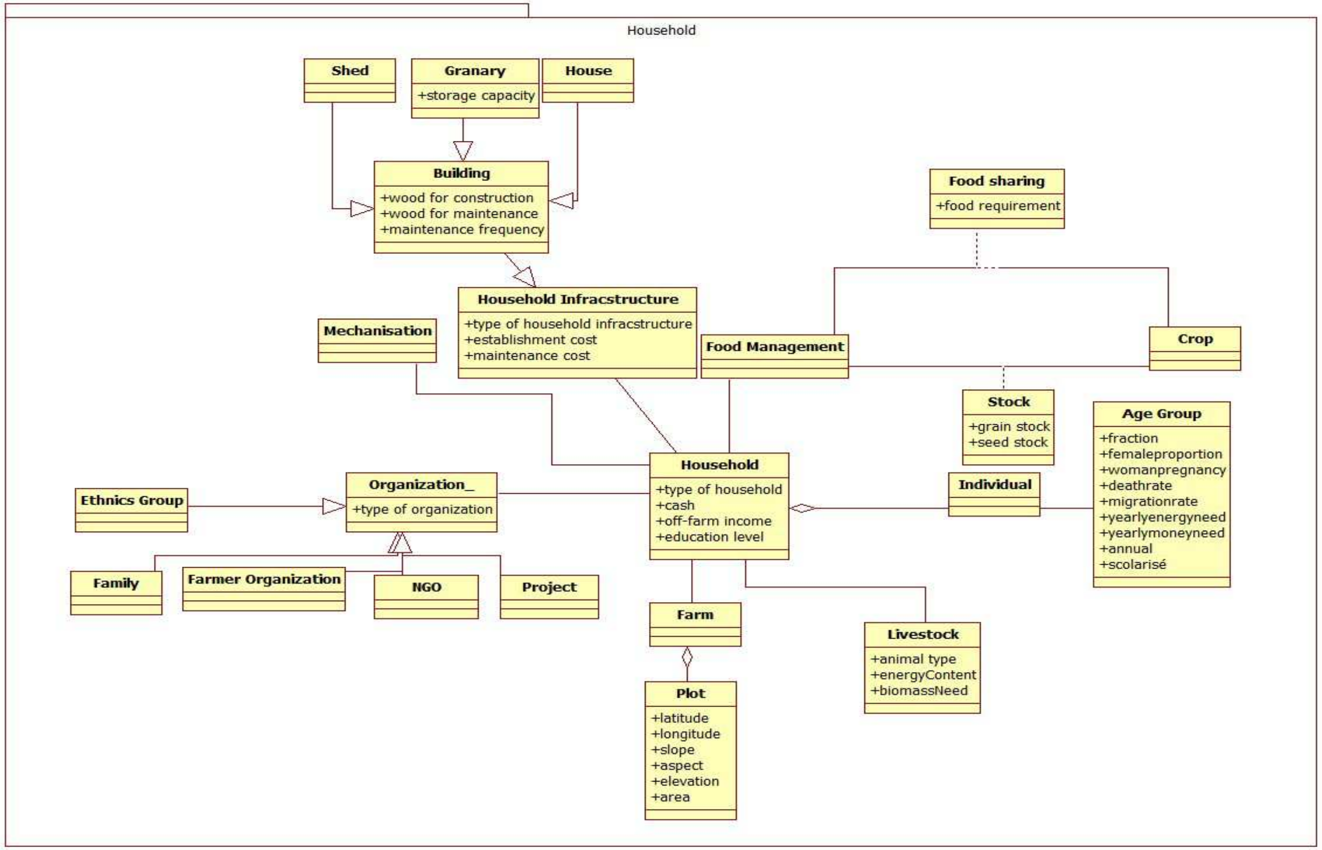


Figure 2: The different components of the generic meta-model for integrated assessment of land use and land management.



s and

Figure 3: A generic meta-model of household representation

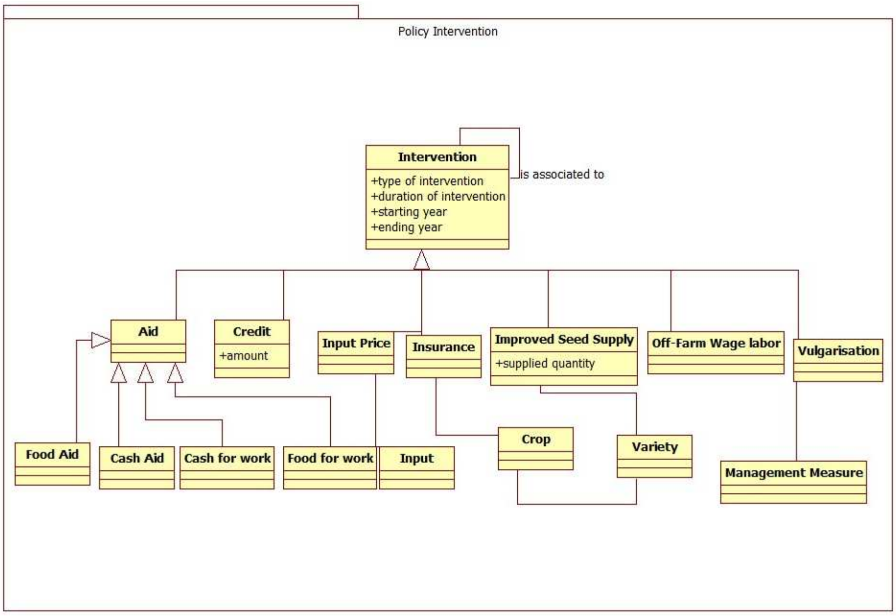


Figure 4: UML representation of policy interventions

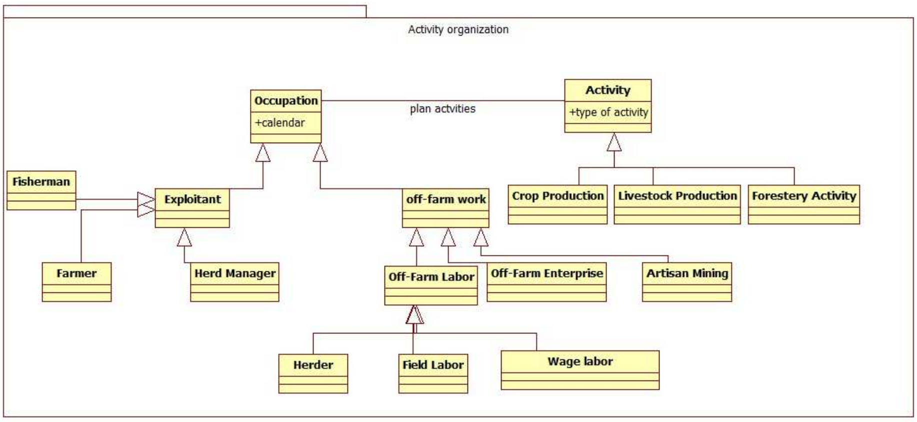


Figure 5: UML representation of household occupations

4. Discussion & Conclusion

4.1. Formalizing the need of a model

According to Landais et Deffontaines (1987), a model is a “theoretical and finalized representation of a reality formulated on the basis of situated observations, of a predefined framework that will then be applied to study cases and permits to give representations quickly”. A model serves to establish structural relationships and functions existing between the factors that one would like to analyze. The objective is to determine the type of relationships existing between these factors and the weight of each factoring the relationships (Parker *et al*, 2001). A model does not exist if it is only about a goal, an objective, which can be problem solving, decision-support or simply experimentation (Roy, 1992; Le Bars 2003). This definition adopts an operational standpoint, thereby insisting on the subjectivity and the need for an objective for every model. This definition paradoxically originated from geographers, who explicitly include maps in this definition, whatever the data origin they rely on. The intrinsic objective of a model is therefore to accelerate and/or facilitate the analysis of a subject (Perrot et Landais, 1993).

4.2. Relevance of ABMs in social simulations of rural development issues

Our issue is intrinsically linked to the characteristics of West African locations: these belong to complex societies and ecosystems, whose components are linked together by various interactions, each related to different scientific disciplines. One cannot select a single interaction among all possible ones as the main and determining relationship that conditions the evolution of such systems. These interactions have therefore to be considered as a whole, without which one cannot understand the functioning of this society. An ABM approach is de facto justified because such models are adapted to the context, the concepts and the question:

- ABMs are adapted to the context of "developing" countries: The low availability of quantitative data and the difficulty of launching statistically reliable investigations limit the use of statistical or multi-criteria optimization models. ABMs allow incorporating more easily partial results coming from different sources (agronomic research stations, statistical questionnaires, open interviews, experts interviews, direct observations or theoretical behavior rules) (Berger, 2001; Bousquet *et al.,* 2001; Le Page *et al*, 2004).
- They are relevant for the analysis of social systems that are multi-active, multi-rational and where interactions and relationships play a major role. The agent-based approach can integrate quantitative and qualitative

variables and thus better formalize the combination of disciplines (Rouchier et Requier-Desjardins, 1998; Berger 2000).

- They are relevant through their approach, i.e. a differentiation of accesses to production means and to the related gains. Micro-economic models rest on the explicit choice of an entity but cannot deal with the effects of the interactions between several dozen entities because they are rapidly submerged by the utility functions with several hundred unknowns. Thanks to their emergence capacity, ABMs can be used according to a very empirical approach (Janssen & Ostrom, 2006).
- And finally, we consider as obvious the fact that, for answering a land use issue, the model we consider should be spatialized. Thus, in the ABMs' typology of Gilbert *et al*, (2006 p.149-152), we stand in the category of spatialized and empirical models.

4.3. Facing the cliff of implementing an efficient modelling approach

Simplification vs. Empirism: a practical tension resides between explorers of processes and explorers of reality. The typology of Gilbert (2006) separates models into two groups: the first one is "abstract" where models are theoretical situations focusing on a specific issue, putting apart the general context. The second group is descriptive: such models describe a real situation with all its complexity. As we consider the real West African situations, we clearly stand in the second group. However, the scenarios we consider to implement, with not yet land policies are closer to abstract models given the calls on prospective theories.

Exploring vs. decision support: Along the inherent objective of any model to explore the variability of a reality through its virtual formalization, modelling for West African issues implies that it has an applicable objective, i.e. for a development issue. Practically, such an objective could not be overcome once one should understand that any funding for research programs do have links with development institutions, which aims and goals are to mitigate issues related to developing countries. We support the idea that an *ex ante* structured formalization of the hierarchy and the sequence of the tasks to be assessed can mitigate such a constraint.

Modelling interdisciplinary processes: beyond the traditional mantra for interdisciplinary, the regularity of the failure of interdisciplinary modelling projects questions the capacity for human scientists to overcome inherent paradigms and points of view belongings to each discipline, i.e. scientific crispation, and affective and institutional brakes to such processes, i.e. position crispation. We do support as well the idea that an *ex ante* formal brainstorming along resilient methods of conceptual sharing such as ARDI (Etienne *et al*, 2011) may mitigate such a constraint.

References

Belem, M., Manlay, R., Müller, J.-P., Chotte, J.-L., 2011. CaTMAS: a multi-agents model to simulate the dynamics of carbon resources of West African villages. *Ecological* Modelling 222, 3651–3661.

Berger, T., 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agr.Eco.* 25, 245–260.

Berger, T., 2000. Integrating approaches for natural resource management and policy analysis. Introductory remarks based on experiences with MAS, in: *Integrating Approaches for Natural Resource Management and Policy Analysis: Bioeconomic Models, Multi-Agent Systems and Cellular Automata. XXIV.International Conference of Agricultural Economists (IAAE)*, pp. 1–23.

Bousquet, F., Lifran, R., Tidball, M., Thoyer, S., Antona, M., 2001. Agent-based modelling, game theory and natural resource management issues. *JASSS* 4.

Etienne, M., Toit, D.D., Pollard, S., 2011. ARDI: a co-construction method for participatory modelling in natural resources management. *Ecology & Society* 16, 44.

Gérard, B., Buerkert, A., 2001. Estimation of spatial variability in pearl millet growth with non-destructive methods. *Expl.Agric*. 37, 373–389.

Gilbert, N., 2006. Sciences sociales computationnelles: simulation sociale multi-agents, in: Amblard, F., Phan, D. (Eds.), *Modélisation et Simulations Multi-Agents: Application Pour Les Sciences de l'Homme et de La Société*. pp. 141–159.

Herrmann, S., van de Fliert, E., Alkan-Olsson, J., 2011. Editorial: Integrated assessment of agricultural sustainability: exploring the use of models in stakeholder processes. *International Journal of Agricultural Sustainability* 9, 293–296.

Janssen Marco A., Ostrom Elinor, 2006. Empirically Based, Agent-based models. *Ecology & Society* 11, 24–37.

Landais, E., Deffontaines, J.-P., 1987. Les pratiques des agriculteurs. Point de vue sur un courant nouveau de la recherche agronomique. *Etudes rurales* 109.

Lavigne-Delville, P., 1998. Harmonising Formal Law And Customary Land Rights In French-Speaking West Africa, in: *Politique Des Structures et Action Foncière Au Service Du Développement Agricole et Rural.* CNASEA, p. 32.

Le Bars, M., 2003. *Un Simulateur Multi-Agent pour l'Aide à la décision d'un Collectif : Application à la gestion d'une ressource limitée agro-environnementale* (phD Computer programming). Université Paris IX-Dauphine, Paris, France.

Le Bris, E., Roy, E.L., Mathieu, P., 1991. *L'appropriation de la terre en Afrique Noire, Manuel d'analyse, de décision et de gestion foncières.* Karthala, Paris, France.

Ostrom, E., 2009. Design Principles of Robust Property-Rights Institutions: What Have We Learned?, in: *Property Rights and Land Policies.* K. Gregory Ingram, Yu-Hung Hong, Lincoln Institute of Land Policy, Cambridge, Ma, USA.

Page, C.L., d' Aquino, P., Etienne, M., Bousquet, F., 2004. Processus participatifs de conception et d'usage de simulations multi-agents: Application à la gestion des ressources renouvelables. *JFSMA*, pp. 33–46.

Parker, D.C., Berger, T., Manson, S.M., 2001. Agent-Based Models of Land-Use and Land-Cover Change : Report and Review of an International Workshop, in: McConnell, W.J. (Ed.), *LUCC Report Series.* UC Irvine.

Perrot, C., Landais, E., 1993. Comment modéliser la diversité des exploitations agricoles ? : Méthodes d'études en milieu paysan. *Les Cahiers de la recherche-développement* 33, 24–40.

Rouchier, J., Requier-Desjardins, M., 1998. *L'Interdisciplinarité pour la modélisation dans la* *recherche-développement : compte-rendu d'une expérience en cours, une application au pastoralisme soudano-sahélien.* CIRAD / CEMAGREF, Montpellier, France, pp. 1–11.

Roy B., 1992. Science de la décision ou science de l'aide à la décision ? *Revue Internationale de systémique* 6, 497–529.

Sangaré M., Fernandez-Rivera S., Bationo A., Hiernaux P., Pandey Vijay S., 2001. Effets de différents types d'amendements sur le rendement du mil et la fertilité du sol au Sahel. *Cahiers Agricultures* 10, 319–325.

Stringer, L., Dougill, A., 2013. Channelling science into policy: Enabling best practices from research on land degradation and sustainable land management in dryland Africa. Journal of Environmental Management 114, 328-335

Saqalli, M., Gérard, B., Bielders, C.L., Defourny, P., 2011. Targeting rural development interventions: Empirical agent-based modeling in Nigerien villages. *Agr.Sys.* 104, 354–364.