Agent-Based Land Use Models for Teaching, Extension and Collaborative Learning

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Abstract

This chapter describes an agent-based land use modeling approach, called MP-MAS, developed at Hohenheim University. The main focus of this approach is the integration of economic decision-models with biophysical models of water supply and soil fertility at a fine spatial resolution. Short-term production and consumption decisions of agents are represented as mathematical programming problems, whereas longer-term decisions, for example investment and migration, are represented using heuristics. Here, we position the approach in relation to alternative agent-based models of land use and water management and describe empirical applications to Chile, Uganda, Ghana, and Thailand. Based on these practical experiences, we discuss the use of MP-MAS as a tool for collaborative learning and participatory research.

1. Introduction

Multi-Agent Systems (MAS) are increasingly used as a tool to disentangle and explore the complex relationships between land use and land cover change (LUCC), policy interventions and human adaptation. The development and application of these tools has been made possible by the rapid increase in computational power available at modest cost. The strength of agent-based land-use models (MAS/LUCC) lies in their ability to combine spatial modeling techniques, such as cellular automata or GIS, with biophysical and socioeconomic models at a fine resolution.

Multi-Agent Systems are flexible in their representation of human land use decisions and therefore appeal to scholars from diverse backgrounds, such as sociology, geography, and economics (Schreinemachers and Berger, 2006). The behavior of individual actors can be modeled one-to-one with computational agents which allows for direct observation and interpretation of simulation results. Large part of their fascination—especially to scholars who are otherwise skeptical of any attempt to quantify and model human behavior—rests on this intuitive and potentially interactive feature. Scholars from CIRAD, for example, combine MAS/LUCC with role-playing games in which a group of resource users, typically farmers using some common-pool resource, specify the decision rules of computational agents and observe how these rules might affect both people's well-being and their natural resource base (Bousquet et al., 2001; D'Aquino et al., 2003; Becu et al., 2003).

In this paper we reflect on the interactive use of multi-agent models not only for participatory simulation of land-use changes but also for teaching, extension and collaborative learning in general. At Hohenheim University, we used our MP-MAS software for teaching at M.Sc. and Ph.D. levels, taught training courses for water resource managers in Chile and parameterized the MP-MAS model for empirical applications in Thailand, Uganda, Chile and Ghana (Berger, 2001; Berger et al., 2006; Schreinemachers 2006; Berger et al., 2007). MP-MAS distinguishes itself most clearly from most other agent-based land use models in its use of a constrained optimization routine, based on mathematical programming (MP), for simulating agent decision-making. Apart from describing the rationale behind this modeling approach, this paper reports on various case study applications, and the use of the model for collaborative learning and research.

2. Multi-Agent Systems of Land-Use/Cover Change

Multi-Agent Systems models of land-use/cover change (MAS/LUCC) couple a cellular component that represents a landscape with an agent-based component that represents human decision-making (Parker et al., 2002). MAS/LUCC models have been applied in a wide range of settings (for overviews see Janssen 2002, Parker et al., 2003) yet have in common that agents are autonomous decision-makers who interact and communicate and make decisions that can alter the environment. Most MAS applications have been implemented with software packages such as Cormas, NetLogo, RePast, and Swarm (Railsback et al., 2006).

The philosophy of agent-based modeling has always been to replicate the complexity of human behavior with relatively simple rules of action and interaction. In empirical applications to the complexity of land use changes, the question arises how simple these rules need to be? Most applications have used relatively simple heuristics to represent the economic decision-making of agents. Schreinemachers and Berger (2006) argued that agents in such applications might have too limited heterogeneity and adaptive capacity, and henceforth preferred implementing agents with goal-driven behavior based on mathematical programming.

The use of mathematical programming has a long tradition in agricultural economics (Hazell and Norton, 1986), and the precursors of today's agent-based models – so-called adaptive macro and micro systems – were implemented with MP (Day and Singh, 1975). Examples for agent-based land use models using MP are Balmann (1997) and Happe et al. (2006) who analyzed structural change in German agriculture with a software called AgriPoliS. In applications to Chile and Uganda, Berger (2001) and Schreinemachers et al. (2007) applied a modeling framework called Mathematical Programming-based Multi-agent Systems (MP-MAS), which we will present in the following.

3. The MP-MAS approach

In Berger (2001), Schreinemachers et al. (2007) and Berger et al. (2007) we described in detail the model components, parameters and equations of MP-MAS. Our approach shares many characteristics with bio-economic farm household models (see for example, Ruben et al., 2000). There are, however, three important additional features that distinguish MP-MAS from the independent, representative farm modeling approach:

1. Number of farm models: Each real-world farm household is individually represented by a single agent in the model; that is, there is a one-to-one correspondence between real-world households and modeled agents. Monte Carlo techniques have been developed to generate alternative agent populations from random sample surveys (Berger and Schreinemachers, 2006).
2. Spatial dimension: The MP-MAS model is spatially explicit and employs a cell-based data representation where each grid cell corresponds to one farm plot held by a single landowner. Sub-models of water run-off and crop growth are linked to this cell-based spatial framework.

3. Direct interactions: Several types of interactions among agents and their environment are explicitly implemented in MP-MAS such as the communication of information, the exchange of land rights and water resources on markets, the return flows of irrigation water, the irrigation of crops, soil nutrient management and crop growth.

This one-to-one MAS representation is able to capture biophysical and socio-economic constraints and interactions at a very fine spatial resolution. Including this heterogeneity of constraints and interactions of farm agents and their biophysical environment broadens the scope of land-use modeling significantly. Phenomena that conventional models cannot easily address—such as local resource degradation, technology diffusion, heterogeneous policy responses and land-use adaptations—can now explicitly be modeled.

Outline of the model

MP-MAS is a freeware software application developed at Hohenheim University and can be downloaded from http://www.uni-hohenheim.de/igm/. A detailed user manual is available from the same website. MP-MAS was written in C++ programming language and is available for both Unix and Windows operating systems. MP-MAS works with a set of input files that are organized in Microsoft Excel workbooks. These workbooks have a modular structure shown in Table 1. The structure of the mathematical programming matrix is defined in *Matrix.xls* and is generic for all farm agents and all simulation periods. Parameters in this matrix are, however, continuously updated to capture each agent's decision problem.

Table 1. The input file structure of MP-MAS

Nr.	Input file	Explanation	Function	
1	ScenarioManager	Contains VBA macros that covert Excel workbooks to ASCII format and manages simulation experiments	To set up scenarios and run the model	Non-optional
2	BasicData	Contains basic parameter values applicable for multiple modules		
3	Matrix	The programming matrix (Mixed Integer Linear Program or MILP)	Simulates agent decision-making	
4	Population	Used to generate agent populations	Define initial agent characteristics	
5	Map	All spatial information including the location of agents and plots		
6	Network	Connects agents by an innovation network and gives details about each innovation		
7	Demography	Specifies the life span of agents, fertility, mortality, and available labor hours	Define the changes over time (e.g., human ageing, tree and livestock growth, price changes)	
8	Market	Market prices (exogenous price information)		
9	Perennials	Specifies the time related attributes of perennial crops		Optional
10	Livestock	Livestock attributes		
11	Soils	Crop yields and soil dynamics	Endogenous biophysics (soils, water, crop yields)	
12	Routing	Water distribution		
13	CropWat	Crop yields as a function of crop water supply		

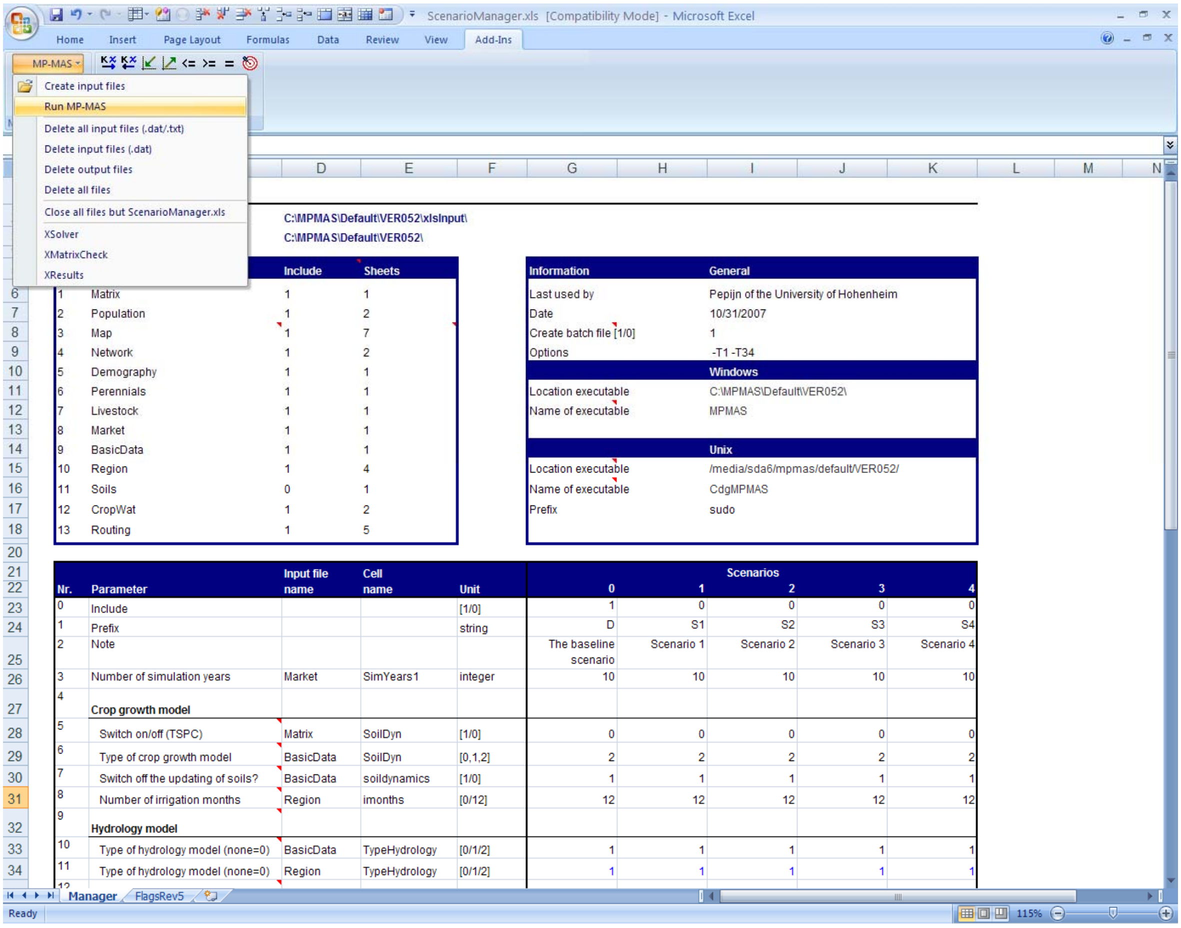
Three files define the initial conditions of the agent population: *Population.xls* defines the agents' resource endowments and household composition, *Map.xls* defines all spatial information (location of farmsteads, plots, soils, watersheds, etc.), and *Network.xls* defines the characteristics of agriculture-related technologies. Four subsequent input files define the dynamics over time: *Demography.xls* defines the labor supply, fertility rates, mortality rates, and food requirements. *Perennials.xls* defines the growth rates of perennials (e.g. fruit orchards, timber) and the input requirements over the age of the orchard. *Market.xls* defines farm-gate selling and buying prices for inputs and outputs such fertilizer, seed, credit interest rates, and food cash crops. In the standard model set-up, market prices for these tradable goods are exogenously given; market prices for non-tradable goods such as land and water are endogenous. Finally, *Livestock.xls* defines for different types of livestock (cattle, pigs, goats) their weight gains, food and pasture requirements, and offspring.

The number of input files can vary between applications depending on what biophysical components (water, soils, or crops) are included. For example, selecting *Soils.xls* makes soil nutrients endogenous in the model and adjusts crop yields depending on the plant nutrient supply. *Routing.xls* defines levels of water inflow and precipitation in the watershed and allocates water rights to agents as a proportion of the inflow that each agent is allowed to divert from the main stream. *CropWat.xls* contains parameters of FAO's CropWat model (Allen et al. 1998), which translates the difference between water supply and agents' water demands into a crop yield reduction.

The policy relevance of the model comes from the use of scenarios (Berger et al., 2006). First a baseline scenario is set up that best reflects the current situation and current drivers of change. Then alternative scenarios are set up that alter some of the basic assumptions, for example, by assuming that soil fertility will not decline. The alternative scenario is then compared to the baseline scenario and the difference in outcomes between both scenarios can then be attributed to assumption that was relaxed. Scenarios are set up in *ScenarioManager.xls* by defining the name of the input file, the name of the parameter, and its alternative value.

Figure 1 shows the interface and the Visual Basic macros (included as an Excel add-in) that allow the user to convert the Excel input files and run the model.

Figure 1. Scenario Manager in MP-MAS (Screenshot)



Applications

MP-MAS has been applied to a variety of case studies in Chile (Berger, 2001), Uganda (Schreinemachers *et al.*, 2007; Schreinemachers, 2006), Ghana, and Thailand (**Table 2**). Other applications to Vietnam and Germany are in the pipeline. Applications to Uganda and Thailand have been small-scale applications at a village or sub-catchment including relatively few agents, while applications to Chile and Ghana have been large scale applications at the level of watersheds and including thousands of agents.

Table 2. Applications using MP-MAS

	Application	No. of farm agents	Spatial dimension		Temporal dimension		Type of agriculture
			extent [km²]	resolution [m]	duration [years]	time step [days]	
1	Chile, Maule basin	3,592	5,300	100	20	30	Market-oriented and commercial
2	Ghana, White Volta basin	34,691	3,779	100	15	30-365 *	Semi-subsistence; Rice, Millets, maize, onion and tomato
3	Uganda, southeastern	520	12	71	16	365	Semi-subsistence; maize, cassava, bean and plantain
4	Thailand, northern uplands	1229	140	40	15	30-365 *	Commercial vegetable and fruit production

In all case studies, research questions related to the interaction between the economic and biophysical sub-systems at the farm household level (**Table 3)**. The objective of the Uganda application was to assess the effect of high-yielding maize varieties on soil nutrient dynamics and economic well-being. The agent-based approach gave a detailed assessment of distributional consequences and let to the conclusion that although poverty could be substantially reduced, the incidence ratio of households below the poverty line would still be 20 percent.

Empirical parameterization

Robinson *et al.* (2007) compared five empirical methods for building agent-based models in land use science: sample surveys, participant observation, field and laboratory experiments, companion modeling, and GIS and remotely sensed spatial data. The empirical base of MP-MAS is mostly random sample surveys of farm households and GIS data, both of these are used to define the initial conditions of the model (Berger and Schreinemachers, 2006). Addition parameters, mostly related to the dynamics of the model, are based on secondary data, qualitative data from field observation, and feedback from stakeholders. For instance, fertility and mortality levels are obtained from statistical agencies, crop yield response from field experiments, while agent interactions can be based on qualitative field observation.

Table 3. Model features of each application

Application	**Objective**	**Economic component**	**Biophysical component**
1. Chile	Provide information to water resource managers (small and large-scale infrastructure projects)	Detailed production functions especially on irrigation methods (MP with 1119 activities, 224 constraints).	Crop growth under water deficits. Spatial distribution of surface water flows.
2. Ghana	Land and water use mostly under rainfed conditions. Test the profitability of irrigated agriculture	MP contains 752 activities and 250 constraints. Includes a detailed expenditure system	Model simulates the water supply and water distribution with a feedback to crop yields
3. Uganda	To disentangle the relationship between technology adoption,	Detailed production functions; 2350 activities, 560	Soil nutrients (N, P, K) and organic matter are endogenous and affect

	soil nutrients, and poverty levels.	constraints. Includes a detailed expenditure system.	crop yields.
4. Thailand	The ex-ante assessment of technology adoption and sustainability strategies.	Based on gross-margin analysis; 53 activities and 60 constraints.	Model simulates the water supply and water distribution with a feedback to crop yields.

4. Collaborative research and learning

As argued above, one of the key advantages of agent-based modeling is the one-to-one correspondence of real-world and computational agents, which facilitates participatory simulation and model-enhanced learning (e.g. Becu et al., 2007). Using agent-based land use models effectively—so that model users receive early warnings, share their system understanding and improve the outcomes of their land-use decisions (Hazell et al., 2001)—poses a number of challenges that have not been fully resolved yet (see for example von Paassen (2004) who reports mixed success for applications of MP models in developing countries). Based on our practical knowledge of using MAS/LUCC models, we reflect on the following critical issues: (i) participatory techniques for model validation; (ii) building trust in model results; (iii) using MP-MAS for agricultural extension; and (iv) development of teaching and training programs.

Participatory techniques for model validation

According to our recent experiences in the CGIAR Challenge Program on Water and Food (see project website http://www.igm.uni-hohenheim.de), MP-MAS has a clear advantage over other integrated modeling approaches we have applied before, for example, aggregate regional land use models. Single-agent models for representative farm households can be constructed and validated jointly with stakeholders in interactive model validation rounds. We first collected farm-specific data on factor endowments such as labor, land and water, and processed these data for a standalone version of MP-MAS. Using the Excel workbook *Matrix.xls*, we calibrated each single-agent model to replicate current land use decisions and performed sensitivity tests together with stakeholders. Through what-if scenarios, for example, how do you adjust your land use if you receive less irrigation water, we could elucidate additional constraints the farmers actually faced and that were originally not included in *Matrix.xls*. The single-agent models were then gradually improved until sufficient model fit for each of the representative farm households was reached. In a second step, the full agent model for the study area was calibrated and validated, using the Monte Carlo approach as described in Berger and Schreinemachers (2006). In our experience, the use of standardized questionnaires is an efficient way of collecting basic agent data on agricultural land-use. The alternative of stakeholder group interviews, as used by other scholars (see Robinson et al., 2007) is much more time-consuming.

Building trust in model results

The interactive modeling rounds for parameter testing and model validation can help building trust in the simulation results of MP-MAS. Since farmers and water managers are directly involved in compiling the model database and performing the sensitivity analyses, they become familiar with the model and its interfaces. Results from special model computations, for example of individual water shadow prices, can be compared with local data and experience and create confidence in the model if the results are plausible. Typically, testing and calibrating of MP-MAS requires more than one modeling round and might demand additional time if unforeseen constraints need to be included. Our impression from applying MAS models with many feedback rounds is that stakeholders and potential model users are prone to losing interest if these rounds consume much of their time. The interactive modeling rounds should therefore generate information that is perceived as immediately useful by stakeholders. In case of market-oriented farm household such information typically involves estimates of crop yields, farm profitability, and household income; in case of water managers it involves minimum river flows, average water uptake and water use efficiency per irrigation section.

Using MP-MAS for agricultural extension

MP is part of planning methods taught in farm management schools and is used in agricultural extension. Standard farm decision problems such as partial budgeting, investment and income analysis can be directly addressed by the tools incorporated in MP-MAS, making use of the database that has to built up for the model application. Our experience is that workers in farm extension programs can therefore be convinced with relative ease of using the single-farm features of MP-MAS. The practical challenge, however, is the maintenance and adaptation of the MP-MAS input files, which requires some minimum knowledge in database management and MP. To address this challenge, we use the ubiquitous software MS-Excel for input/output operations and have formed a group of advanced model users that are trained in using MP-MAS.

Development of teaching and training programs

MP-MAS requires, as all other software, teaching and training. We started developing specific programs targeted at various potential user groups, ranging from introductory demonstrations in a few days to a series of workshop sessions held over one year. At Hohenheim University, we offer consecutive courses on “Farm-Level Modeling” and “Land-Use Economics” at MSc level and “Advanced Techniques for Land-Use Modeling” at PhD level. The inclusion of agent-based modeling in the curriculum of the Master Study Programs “Agricultural Economics” and “Agricultural Sciences in the Tropics and Subtropics” in Hohenheim has added young scientists to the model developer group and increased the number of empirical research applications as part of dissertation projects. Currently, we are planning to develop on-line resources to be inserted in the distance learning program of the “Global Open Food and Agriculture University” (GOFAU).

5. Conclusion

MP-MAS is a software application for agent-based modeling that through the use of mathematical programming represents goal-driven behavior of farm agents. Biophysical models simulating soil fertility dynamics, water supply, or crop yields have been spatially integrated with agent decision-making through the use of GIS layers. The method is suitable for research questions related to the interaction of economic and biophysical sub-systems and to assess distributional consequences of policy and environmental change. MP-MAS has been applied to case studies in Chile, Uganda, Ghana, and Thailand and valuable experiences have been gained about using MP-MAS in participatory settings. Research is ongoing; the evaluation of the effectiveness of the MP-MAS approach in improving land-use decisions as envisaged in the CGIAR Challenge Program on Water and Food is still not completed. Our conclusion is that initial results form using MP-MAS in interactive settings are promising but more methodological research is needed to fine-tune and insert MP-MAS as an effective tool into land-use planning and farm extension programs.

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