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Multi-Agent Models for Teaching, Extension and Collaborative Learning

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Abstract: This paper 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.

Keywords: Natural Resource Use; Participatory Simulation; Mathematical Programming

1. INTRODUCTION

Multi-Agent Systems (MAS) are increasingly used as a tool to disentangle and explore the complex relationships between land use including water resources, 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 lies in their ability to combine spatial modeling techniques, such as cellular automata or geographical information systems (GIS), with biophysical and socioeconomic models at a fine resolution.

MAS 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 combine MAS 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 change but also for teaching, extension and collaborative learning in general. At Hohenheim University, we use our MP-MAS software for teaching at M.Sc. and Ph.D. levels, teach 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 other agent-based land use models in its use of a constrained optimization routine, based on mathematical
programming, 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 FOR LAND USE MODELING

Multi-Agent Systems for land use modeling couple a cellular component that represents a landscape with an agent-based component that represents human decision-making [Parker et al., 2002]. Models of this type 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 multi-agent systems 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 mathematical programming [Day and Singh, 1975]. Examples for agent-based land use models using mathematical programming are Balmann [1997] and Happe et al. [2006] who analyzed structural change in German agriculture with software called AgriPoliS. In applications to Chile and Uganda, Berger [2001] and Schreinemachers et al. [2007] developed software called Mathematical Programming-based Multi-agent Systems (MP-MAS), which we will present in the following.

3. THE MP-MAS APPROACH

3.1 Model features

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:

- **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].

- **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.

- **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.

MP-MAS is freeware software 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++ 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.

### 3.2 Applications

MP-MAS has been applied to a variety of case studies in Chile [Berger, 2001], Uganda [Schreinemachers et al., 2007], Ghana, and Thailand (Table 1). Other applications to Vietnam and Germany are in the pipeline. Applications to Uganda and Thailand have been small-scale applications at village or micro-catchment level 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>
<thead>
<tr>
<th>Application</th>
<th>No. of agents</th>
<th>Spatial dimension</th>
<th>Temporal dimension</th>
<th>Type of agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>extent [km²]</td>
<td>resolution [m]</td>
<td>duration [years]</td>
</tr>
<tr>
<td>1 Chile, Maule basin</td>
<td>3,392</td>
<td>5,300</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>2 Ghana, White Volta basin</td>
<td>34,691</td>
<td>3,779</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>3 Uganda, southeastern</td>
<td>520</td>
<td>12</td>
<td>71</td>
<td>16</td>
</tr>
<tr>
<td>4 Thailand, northern uplands</td>
<td>1,229</td>
<td>140</td>
<td>40</td>
<td>15</td>
</tr>
</tbody>
</table>

Note: * Components of the model have different time steps. The decision-making follows an annual sequence while crop water requirements, irrigation water supply, and rainfall are specified on a monthly base.

In all case studies, research questions related to the interaction between the economic and biophysical sub-systems at the farm household level (Table 2). For example, 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.

### 3.3 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,
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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]. Additional 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 2. Model features of each application

<table>
<thead>
<tr>
<th>Application</th>
<th>Objective</th>
<th>Economic component</th>
<th>Biophysical component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chile</td>
<td>Provide information to water resource managers (small and large-scale infrastructure projects)</td>
<td>Detailed production functions especially on irrigation methods (agent decision model with 1119 activities, 224 constraints).</td>
<td>Crop growth under water deficits. Spatial distribution of surface water flows.</td>
</tr>
<tr>
<td>2. Ghana</td>
<td>Land and water use mostly under rainfed conditions. Test the profitability of irrigated agriculture</td>
<td>Agent decision model contains 752 activities and 250 constraints. Includes a detailed expenditure system</td>
<td>Model simulates the water supply and water distribution with a feedback to crop yields</td>
</tr>
<tr>
<td>3. Uganda</td>
<td>To disentangle the relationship between technology adoption, soil nutrients, and poverty levels.</td>
<td>Detailed production functions; 2350 activities, 560 constraints. Includes a detailed expenditure system.</td>
<td>Availability of soil nutrients and organic matter is endogenous and affects crop yields.</td>
</tr>
<tr>
<td>4. Thailand</td>
<td>The ex-ante assessment of technology adoption and sustainability strategies.</td>
<td>Based on gross-margin analysis; 53 activities and 60 constraints.</td>
<td>Model simulates the water supply and water distribution with a feedback to crop yields.</td>
</tr>
</tbody>
</table>

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]. Applying 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 mathematical programming models in developing countries). Based on our first practical experiences of applying multi-agent simulation with stakeholders, 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. More formal results will become available soon from our monitoring and evaluation system that we implemented in Ghana and Chile.

4.1 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. First, we collected farm-specific data on factor endowments such as labor, land and water, and processed these data for a standalone version of MP-MAS. Then 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 the model. 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.

4.2 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 behavioral constraints need to be included. Our impression from applying multi-agent simulation 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.

4.3 Using MP-MAS for agricultural extension
Mathematical programming 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.

4.4 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 of 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 distance learning programs.

5. CONCLUSIONS

MP-MAS is a software 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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