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Agent-based Modelling in the Agricultural Economics Tradition of Recursive Farm Modelling and Adaptive Micro-Systems

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Abstract: Among model developers, a consensus has grown that environmental simulation models should ideally give a balanced representation of the economic, environmental, as well as social dimensions of a given system. Agent-based models or multi-agent systems (MAS) have been suggested as one possible balanced approach to capture especially the externalities and feedbacks between resource users in Social-Ecological Systems. Following the definition of Parker et al. (2002), multi-agent 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. Various layers of landscape and agent properties and processes are combined into a spatial, cell-based framework, for example plots that produce biomass and farm-holdings that make land-use decisions. The behaviour of each landscape unit and each agent is represented by specific modules such as crop growth modules and agent decision modules. Parker et al. (2002) distinguish the following classes of MAS/LUCC: (1) abstract, (2) experimental, (3) historical, and (4) empirical applications. For example, Companion Modelling, which combines MAS with group discussions and role-playing games, falls into class (2), whereas agent-based modelling in the agricultural economics tradition falls into class (4). The paper discusses the particular purpose of the agricultural economics modelling approach, the real-world system entities and interactions captured, its data requirements, methods for uncertainty and sensitivity testing, and its applicability for interactive modelling and policy assessment.

***Keywords**:* Bioeconomic modelling; Multi-Agent System; Mathematical Programming; Scenario-based policy analysis.

1 INTRODUCTION

In this paper, we describe the agent-based modelling approach that stands in the agricultural economics tradition of Recursive Farm Modelling and Adaptive Micro-Systems, using Mathematical Programming.

1.1 Modelling Tradition in Agricultural Economics

There is a long tradition of simulation modelling in Agricultural Economics that dates back to the pioneering work of Richard Day and Theodor Heidhues in the 1960s, when the first Linear Programming (LP) models were developed for policy analysis. LP is a planning approach used in farm management that helps finding the assignment of farm resources (land, labour, machinery) to various land-use options (grow crops, graze livestock) such that certain goals (increase income, reduce risks) can be achieved as best as possible. While the purpose of LP was initially *prescriptive*, giving farmers recommendations on how to improve their

productivity, soon after LP models were also developed for *descriptive* and *predictive* purposes, e.g. for simulation of actual farmer behaviour and especially for policy assessments. Because of their strong empirical foundation, agricultural economists usually take a pragmatic stance and implement some form of *bounded rationality* in their simulation models, i.e. deviate from profit-maximisation and market equilibrium of Neoclassical Economics. Day & Singh (1975), for example, developed a so-called adaptive macro and micro system, in which LP models representing real-world farmers were solved recursively over time and gradually responded to changes in agricultural prices and policy interventions (an update of this work can be found in Day, 2008).
After a decline in interest for simulation modelling in Agricultural Economics during the 1980s, Balmann (1997) developed an agent-based farm LP model and was followed by Berger (2001) who drew on Balmann's work and began implementing MAS with hydrological and economic modules. Other examples of LP-based bioeconomic models can be found in Janssen & van Ittersum (2007). The latter, however, do not simulate interactions between farms and are sometimes referred to as representative farm models or micro-simulation models.

1.2 Multi-Agent Systems of Land-Use Change

Following the definition of Parker et al. (2002), multi-agent 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.

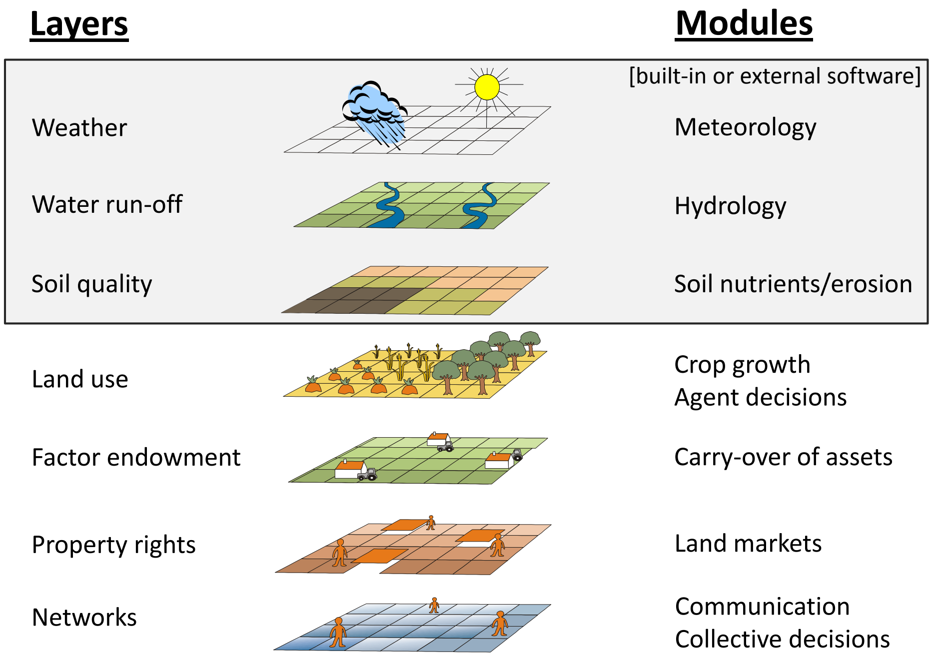

Figure 1: Architecture of MAS/LUCC

Figure 1 shows the typical architecture of MAS/LUCC (Note: layers refer to the "attributes" of landscape and agent entities, modules refer to the "methods" how these attributes are changed). Various layers of landscape and agent properties and processes are combined into a spatial, cell-based framework, for example plots that produce biomass and farm-holdings that make land-use decisions. The behaviour of each landscape unit and each agent is represented by specific modules such as crop growth modules and agent decision modules. This one-to-one correspondence of real-world entities and model entities and–at the same time–explicit consideration of agent-agent and agent-environment interactions is unique of MAS/LUCC. It goes beyond the capabilities of micro-simulation approaches that are specified at a similar level of aggregation, but do not capture the interactions between system entities. Furthermore, by representing land users and their biophysical environment, MAS/LUCC implement a holistic modelling approach that allows for consideration of both economic goals and environmental sustainability.

2 CHARACTERIZATION OF MODEL APPROACH

In this section, we describe in more detail the MAS/LUCC approach in the Agricultural Economics tradition, which we abbreviate here as AgEcMAS. Recent applications of this approach are on irrigation management (Berger et al., 2007), soil fertility (Schreinemachers et al., 2007), technology adoption (Schreinemachers et al., 2010) and structural change (Freeman et al., 2009; Happe et al., 2009).

2.1 Purpose

The purpose of AgEcMAS is to improve scientific understanding, prediction and policy decision making related to agricultural systems. It should be emphasised, however, that “prediction” in this context implies “scenario analysis” and not “forecast” in the traditional sense. Given the large uncertainty embodied in model architectures and parameters as well as the impossibility of forecasting human behaviour and certain environmental events, simulation experiments with AgEcMAS can only help to explore the possibility space of land-use adaptation. Since AgEcMAS simulate the policy response of all farm holdings, it is possible to elucidate the distributive effects of specific policy interventions and to identify winners, losers and feasible compensations. This distributive analysis is an important contribution to cost-benefit evaluations in Agricultural Economics that is rather neglected in conventional policy analysis modelling (von Braun, 2005).

Because of the strongly applied modelling tradition in Agricultural Economics, AgEcMAS contain large amounts of empirical data and system knowledge. National statistical offices, farm accounting networks and specific model consortia, as well as FAO, Worldbank and other international organisations have spent considerable efforts in building agricultural data bases. The same applies for software packages that have been developed for simulation of sub-system dynamics, for example crop growth, soil and hydrology models. Without connecting to these data and software resources, costs for model development become very high and models lack credibility in the research community.

2.2 Breadth and depth of issues being addressed

The primary focus of AgEcMAS, like most agricultural economics models, is to predict the adaptation of agriculture to situations not yet observed in reality, e.g. under altered environmental and economic conditions or policy regimes. Contrary to other policy analysis models, AgEcMAS allow for two perspectives of analysis at the same time:

(1) From the macro perspective, analysis focuses on changes in agricultural supply, land use, factor demand and associated impacts on food security, landscape functions and agro-ecosystem services. AgEcMAS can improve macro analysis compared to standard models, whenever individual-level processes or interactions between farms are relevant but cannot easily be captured by aggregated functions (e.g. diffusion of innovations, land markets, irrigation water use and erosion).

(2) From the micro perspective, success or failure of farm holdings and households to cope with changing conditions can be analysed. Agent heterogeneity can be captured with relative ease when using a Monte-Carlo parametrisation approach such as in Berger & Schreinemachers (2006). While AgEcMAS can be used for micro-simulation as standard bioeconomic farm models, they additionally reflect the consequences other agents' behaviour and thus highlight the effects of competition, cooperation and exchange.

Simulation-based analysis can integrate both perspectives and identify suitable policy interventions to achieve certain societal objectives, while also revealing the distributional consequences (farm income, food security, environmental sustainability) that may have to be addressed by complementing policy measures.

2.3 Level of spatial and temporal detail required

In order to provide useful insights for adaptation and policy analysis, AgEcMAS must fulfil the following requirements:

- As technical and financial constraints are highly important for farmer adaptation and policy response, these models should have a solid microeconomic footing and sufficient detail in terms of farm management and agronomic conditions. This is a critical issue because the economic intuition behind conventional environmental modelling results is sometimes not clearly laid out.
- Policymakers, land-use planners and farm extension agencies are interested in predicting the diffusion of innovations and in assessing policy implications, which implies modelling farmer expectation, learning and risk behaviour. Heterogeneity in behavioural constraints should therefore be captured by farm simulation models.
- Behavioural constraints often reflect the cumulative effects of own experience and observation of neighbours' experiences. The exchange of information about new technologies and adaptation strategies is therefore one important type of farmer interaction that should be captured in AgEcMAS.
- Spatial interactions are often very important for agricultural development and land-use adaptation. The exchange of locally available factors of production, notably land and water, sets limits to farm growth and structural change. Endogenous price formation for land and water might then be required for mid-term adaptation analysis.
- Environmental interactions and feedbacks can be decisive for land-use adaptation, for example the occurrence of flooding events and soil erosion or the invasion of new pests and diseases. Since most of these environmental feedbacks are highly location-specific, sufficiently disaggregated model parametrisation and inclusion of model feedback are required.
- For longer-term adaptation analysis some additional dynamics must be captured, for example life cycle and demography, rural-urban linkages, and agricultural versus non-agricultural growth.

2.4 Data Requirements

The model entities in AgEcMAS are specified at the micro-level and have therefore data requirements comparable to bioeconomic farm models (Janssen & van Ittersum, 2007). In most cases, data requirements of agents can be met by farm sample surveys, key informant interviews and other forms of data collection developed in the social sciences (Robinson et al., 2007).

In addition, data are needed for the spatial set-up of agent activities and for the parametrisation of agent-environment and agent-agent interactions. Spatial data for AgEcMAS can be derived from available map material, for example land suitability maps, land cover classifications based on satellite images, air photos and cadastre data. Biophysical data such as water availability, soil nutrient levels etc., are often generated with biophysical simulation models, stored in Geographical Information Systems (GIS) and then used for parametrisation of the cellular model component. Spatial data are ideally combined with direct measurements in the field ("ground-truth"). Data for agent-environment interactions are usually derived from some form of production function or activity analysis, as standard in bioeconomic models. Agent-agent interaction data, in contrast, are not standard and must therefore be collected through key informant interviews or expert opinion. Recently, attempts have been made to gather agent interaction data from economic experiments, either under laboratory or field conditions. Another approach to finding interaction data is initialising the model with some ad hoc values and then calibrating it until a sufficient match between simulated and observed interaction outcomes has been reached.

It is a challenge, however, to collect data on the future adaptation behaviour of agents. This is generally important for all longer-term scenario analyses that are "out-of-sample" simulations, and is not unique of AgEcMAS. New situations might unfold in a few years that are not captured in land users' experiences and decision rules, which will then be changed to cope with unforeseen events. Expert opinion might be the only starting point for model parametrisation but should be complemented with local knowledge or stakeholder insights. Berger et al. (2010) made use of the one-to-one-correspondence of real-world farmers and computational agents and developed a participatory simulation approach with interactive modelling sessions (see also Becu et al., 2003). A representative sample of real-world farmers is selected for in-depth surveys in a first visit, and single-agent models are developed for each individual farm. The single-farm model results are compared to the survey results, and disparities between simulated and observed data are discussed with the individual farmers in a second visit. Important aspects that have not yet been included in the model can then be incorporated and subsequently be used to improve parametrisation. In this way, the model is validated iteratively, until the most important variables and constraints have been quantified. After validation of current conditions, the single-farm model is used for interactive scenario analysis. Farmers are confronted with new situations, for example changes in water availability, and asked for their adaptation behaviour. The same scenarios are also run with the single-farm models, and simulation results are compared to farmer verbatim. In case of disparities, model parameters are again improved and finally included into the full AgEcMAS model.

2.5 Capacity to address uncertainty and assess model credibility

Although uncertainty and sensitivity analysis are well-established methods in the literature of simulation modelling, Janssen & van Ittersum (2007) found only few cases of application in their review of bioeconomic farm models. Only in 8 out of 48 modelling studies, results from sensitivity analysis were reported. Likewise, calibration and validation of these models was often very rudimentary compared to biophysical models. This lack of formal testing is difficult to accept and cannot be excused simply by the limited space that journals offer for publication of simulation studies.

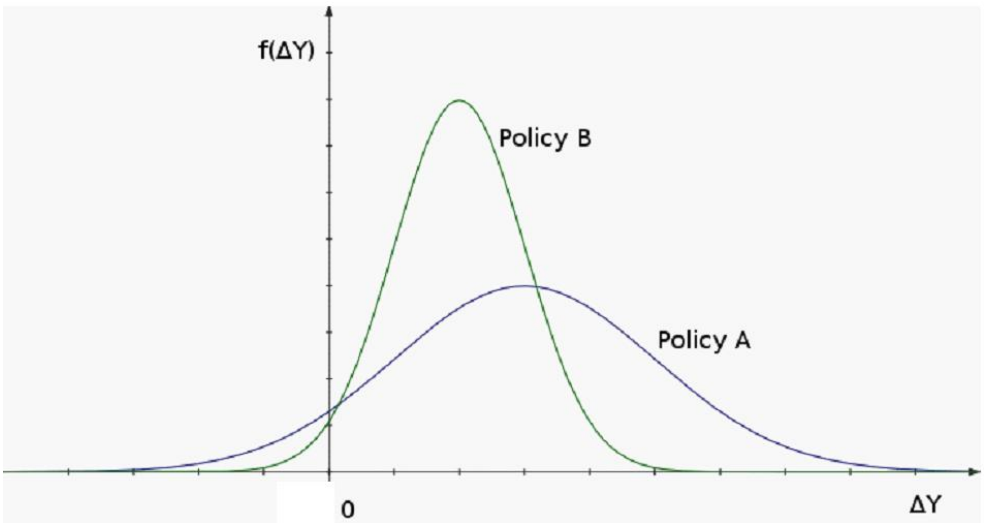

Figure 2: Probability distributions in two policy scenarios

The fundamental difficulty in policy analysis modelling is the limited knowledge of the expected error distribution of predictions, which is required for formal procedures of model selection and evaluation. There has been little research into the theoretically acceptable or even necessary deviation of economic models from observed human behaviour, with the consequence that criteria for model performance can be formulated only in a qualitative manner. In addition, suitable time-series data are largely not available at the farm and plot level and, therefore, change and tracking experiments cannot be undertaken.

With respect to sensitivity analysis of AgEcMAS, sampling-based methods can be applied (e.g. in Schreinemachers & Berger, 2011) in order to provide information on the uncertainty of model outcomes. Sensitivity analysis can then help to identify, which of the uncertain parameters are most important in determining the uncertainty of, for example, the farm income distribution *Y*. For ex ante policy assessment, the outcome variable of interest is typically not *Y* but *ΔY*, the difference in *Y* between the baseline without any policy and a situation where a specific policy intervention *A* or *B* is in place. In contrast to purely statistical model approaches, simulation with AgEcMAS allows “controlling” for all other model parameters, so that the difference between two situations can be reduced to the policy intervention itself. Figure 2 displays the outcome of model uncertainty analysis for this kind of policy assessment.

Because of the detailed process descriptions and the large uncertainty in model structure and model parametrisation, sensitivity testing in AgEcMAS demands considerable more computing power than in conventional policy simulation models. Fortunately, the demand for increased computing power can now be much better met as research groups have started using advanced computing resources and Grid technology. Sensitivity analysis techniques for variable screening and calculation of first-order and total effects are becoming available, which involve specific experimental designs or sampling strategies in order to reduce the number of model evaluations necessary. Also, more efforts are being made to build up household time-series data sets especially for agricultural economics research in the tropics and subtropics.

2.6 Capacity for effective communication and social learning

Quite popular in multi-agent modelling are joint applications of group discussions, role-playing games and participatory computer simulations, which offer opportunities for social learning (Bousquet et al., 2001; Barreteau et al., 2001; Castella et al., 2005). A group of land users, typically farmers jointly using some common-pool resource, specify the decision rules of computational agents and observe how these decision rules might affect both people’s well-being and their natural resource base. *Companion Modelling*, however, involves much more parsimonious modelling of socio-economic and biophysical processes than in Agricultural Economics and is typically applied at the very local scale.

AgEcMAS can also make use of the interactive and participatory features of agent-based simulation. One example is the “Integrating Governance and Modelling” project in the CGIAR Challenge Program on Water and Food (Berger et al., 2007). The project applied MAS for evaluating water shadow prices of farmers and their willingness-to-pay for the construction of a new reservoir in Chile. A key innovation of the research was the development of the decision-support tools in close interaction with multiple stakeholders, including water user associations and members of the irrigation and agricultural administration. This interaction, which was organised in the form of individual consultations, workshops and training sessions, ensured that AgEcMAS simulations addressed the needs and priorities of different stakeholders and took their local knowledge into account (see http://www.uni-hohenheim.de/igm).

3 COMPARISON WITH OTHER APPROACHES

Schreinemachers & Berger (2011) compared MP-MAS, a representative of AgEcMAS, with 8 other simulators of human-environment interactions in agricultural systems. The comparison revealed that MP-MAS with its microeconomic foundation is unique among these simulators in modelling innovation and technological change. It combines social network effects with an economic evaluation of technologies in which agents only adopt if they expect that adoption will contribute to reaching their individual household objectives. Moreover, MP-MAS is the only simulator in which agents update price expectations and can exchange land and water resources on local markets. The comparison also showed that MP-MAS is relatively flexible in its use of biophysical modules. It can either simulate water flows or soil fertility changes; and it can either use a fine or a course temporal resolution, depending on the purpose of the application and the availability of empirical data. Optionally, MP-MAS can be coupled via TCP/IP to external software simulating the hydrology, soil and plant systems.

A major limitation, however, is that current AgEcMAS applications simulate the decision-making of farmers only; other agents such as land-owners and water user associations are represented with highly simplified decision rules. The agent-based model of Becu et al. (2003), in contrast, simulates the decision-making also of other agents such as government agencies, industries, and non-farm households. AgEcMAS applications such as MP-MAS are therefore not suitable for modelling situations in which farmers compete for resources with non-farmers.

Moreover, MP-MAS cannot yet allow for collective action to emerge endogenously. Agent can, for instance, exchange water rights if using the optional water market module, but agents cannot collectively decide to build a new water reservoir for irrigation. The impact of such changes can only be assessed by introducing such change exogenously through the input data of the software and then comparing the simulation outcomes with and without the reservoir. Also, different from the modelling approaches of Becu et al. (2003), Letcher et al. (2006) and Le et al. (2008), agents in MP-MAS cannot encroach into collective forests or open up new land areas. The current version of the software relies on clearly defined ownership rights over pixels; only if agents are given ownership over particular forest pixels can the software simulate their decision to leave it as forest or to convert it to agricultural land. Here again MP-MAS shows its economic foundation and captures the financial aspects of investment and management related to tree crops.

4 CONCLUSIONS AND RECOMMENDATIONS

As was argued in this paper, agent-based simulation has parents and siblings in Agricultural Economics modelling. Recursive farm models, adaptive macro/micro systems and bioeconomic models have been developed for about 5 decades, using Mathematical Programming for the simulation of farmer decision making. The specific purpose of agent-based simulation in this modelling tradition is to understand how agricultural technology, market dynamics, environmental change, and policy intervention affect a heterogeneous population of farm households and the agro-ecological resources these households command. The modelling approach employs scenario-based analysis to explore the impact of these changes and has capacity for participatory simulation and uncertainty testing. A number of techniques and procedures have been developed for empirical parametrisation, external software coupling and effective communication of results.

In the context of environmental modelling, the agent-based agricultural economics approach might be highly suitable for regional and local level simulation studies, where agricultural land users are driven by economic considerations and are connected to markets. The approach has, however, two major limitations: (1) it is confined to simulation of farm holdings and/or rural households, although work is ongoing to include producer organizations and other non-farm agents. As a consequence, the approach is currently not appropriate for modelling situations in which farmers compete for resources with non-farmers; (2) it focuses on individual decisions and not on collective decisions, i.e. it cannot adequately deal with common-pool resources management and similar collective action issues (this is the strength of alternative agent-based approaches such as Companion Modelling).

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