An agent-based simulation model of human-environment interactions in agricultural systems

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Abstract

This paper describes an agent-based software package, called Mathematical Programming-based Multi-Agent Systems (MP-MAS), which builds on a tradition of using constrained optimization to simulate farm decision-making in agricultural systems. The purpose of MP-MAS 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 software is presented using the Overview, Design concepts, and Details (ODD) protocol. Modeling features are demonstrated with empirical applications to study sites in Chile, Germany, Ghana, Thailand, Uganda, and Vietnam. We compare MP-MAS with eight other simulators of human-environment interactions (ABSTRACT, CATCHSCAPE, ECECMOD, IMT, LUDAS, PALM, SAM, and SIM). The comparison shows that the uniqueness of MP-MAS lies in its combination of a microeconomic modeling approach and a choice of alternative biophysical modules that are either coded as part of the software or coupled with it using the Typed Data Transfer (TDT) library.

Keywords: mathematical programming, integrated modeling, multi agent systems, land use cover change, technology adoption, impact assessment
## Software availability

**Name of software:** Mathematical Programming-based Multi Agent Systems (MP-MAS)  
Version 3.0 (April 2010)

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**Hardware required:** 32-bit PC with Windows OS or Linux  
1-10 GB of free disk space (depending on application)  
We recommend using a high-speed processor and at least 4 GB of RAM.

**Software required:** MS Office Excel for constructing input files. IBM OSL\(^1\) as optimization software. STATA SE is recommended for analyzing the simulation output.

**Program language:** C++

**Availability and cost:** Freeware downloadable from: [https://mp-mas.uni-hohenheim.de/](https://mp-mas.uni-hohenheim.de/) including a user guide. A default data set is available online for testing the software. Most of the model features presented here, except the coupling with external software, can be tested by switching specific features on or off in this default version.

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\(^1\) IBM has stopped its development of OSL and transferred the software code to an open source community, called COIN. Work is ongoing to implement COIN in MP-MAS so that it can run be run without OSL.
1 Introduction

Simulation models have become important tools for assessing, \textit{ex ante}, the impact of new technologies, policy interventions and climate change on agricultural systems (\textit{e.g.} Doglioni \textit{et al.} 2009, Gilfedder \textit{et al.} 2009, Wang \textit{et al.} 2010). Among model developers, a consensus has grown that such simulation models should ideally give a balanced representation of the economic, environmental, as well as social dimensions of a given system (Parker \textit{et al.} 2002, Schaldach and Alcamo 2006).

While many simulation models combine economic, environmental and social components at fine resolution, only a few incorporate the dynamic interactions between them (Argent 2004). Incorporating these interactions is required to better capture management options for agricultural systems in which the economic decisions and social interactions of farmers and other land users partly depend on environmental change, and in which the environment changes in response to the decisions and interactions of all land users (Walker 2002). A special case are so-called \textit{Social-Ecological Systems} in which land users create environmental externalities that affect other resource users, for example through water return-flows in irrigation systems or through soil erosion and sedimentation in agricultural landscapes (Janssen and Ostrom 2006).

This paper presents a software package, called Mathematical Programming-based Multi Agent Systems (MP-MAS), that couples dynamic models of farmer decision-making and interactions with various dynamic models of environmental processes, notably water flows and soil fertility changes. The purpose of MP-MAS 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 paper has three objectives. The first is to describe MP-MAS using the ODD (Overview, Design concepts, and Details) protocol developed by Grimm et al. (2006). Recent papers reported on selected aspects of MP-MAS (Berger and Schreinemachers 2006, Schreinemachers and Berger 2006) but a comprehensive description of the software is missing; with this paper we therefore aim to close this gap.

The second objective of the paper is to discuss modeling choices in MP-MAS with regard to empirical research questions and system characteristics. Previous papers presented results from applications of the software (Schreinemachers et al. 2010, 2009, 2007, Berger et al. 2007) but a general discussion of the empirical modeling choices within MP-MAS has not been undertaken so far. The overview of applications to six study sites shows that the optional components in MP-MAS allow users to apply the software to a wide range of research questions, spatial scales, and levels of data availability without having to change the software code.

The third objective of the paper is to position the MP-MAS software package in the recent literature on simulation models of human-environment interactions in agriculture. We compare MP-MAS to eight simulators: ABSTRACT (van Oel et al. 2010), CATCHSCAPE (Becu et al. 2003), IMT (Letcher et al. 2006a, 2006b), SIM (Krol and Bronstert 2007), ECECMOD (Vatn et al. 1999, 2006), LUDAS (Le et al. 2008, 2010), PALM (Matthews 2006) and SAM (Belcher et al. 2004). The comparison shows that the uniqueness of MP-MAS lies in it being an agent-based approach with a strong foundation in microeconomics and farm management theory and optional modules for simulating biophysical dynamics. Because of this, the software is able to assess ex ante how farm households would adapt if economic incentives changed, for example through policy intervention, market dynamics and resource depletion. Another unique feature of MP-MAS is its ability to simulate the diffusion of agricultural innovations by combining a frequency-
dependent communication effect at population level and an economic assessment of costs, benefits, and resource constraints at farm household level.

The remaining four sections of the paper are organized as follows. Section 2 provides background information about the software development and highlights its relationship to bio-economic modeling. After describing the software using the ODD protocol in Section 3, the paper proceeds to give an overview of applications to six study sites in Section 4. This is followed in Section 5 by a comparison of MP-MAS to eight other simulators of human-environment interactions in agricultural systems. In the conclusion we then bring together the proceeding sections by highlighting the novel aspects of the MP-MAS software package.

2 Background

2.1 Development of MP-MAS

The simulation of land use change and adaptation in agricultural systems has a tradition spanning more than forty years. Starting in the 1960s, scholars such as Richard Day and Theodor Heidhues were using recursive linear programming models for farm policy analysis, and implemented the precursors of today’s agent-based models in agriculture – so-called adaptive macro and micro systems (see, for example Day and Singh 1975; an update of this work can be found in Day 2005).

After a decline in interest for simulation modeling during the 1980s, Balmann (1997) developed an agent-based linear programming model and was followed by Berger (2001), who drew on Balmann’s work and began writing the first lines of code for MP-MAS. These two agent-based models have diverged since then, although the underlying concept of representing agent decisions through mathematical programming (MP) remains the same.
Balmann, together with Happe, turned their code into the Agricultural Policy Simulator (AgriPoliS). AgriPoliS has been used to *ex ante* simulate structural change in European agriculture, in response to proposed changes to the Common Agricultural Policy (Happe *et al.* 2009, 2008, 2006). Berger, on the other hand, developed his code into a Multi-Agent System (MAS) of human-environment interactions ( Berger *et al.* 2006), which later got the name MP-MAS. This multi-agent software has been applied to the *ex ante* impact assessment of agricultural innovations and policies, especially in developing countries. Hence, the chief difference is that MP-MAS includes endogenous biophysical dynamics and is tailored to the assessment of agricultural innovations with most applications to developing countries, whereas AgriPoliS is a more economic simulation model tailored to assessing structural change with all applications to European countries.

Both MP-MAS and AgriPoliS fall into the class of Multi-Agent Systems applied to Land-Use/Cover Change (MAS/LUCC), defined as simulation models that couple a cellular component representing a geographical landscape with an agent-based component representing human decision-making (Parker *et al.* 2003, Robinson *et al.* 2007).

2.2 Extensions to bio-economic modeling

MP-MAS shares features with bio-economic farm household models, such as those developed by Schuler and Sattler (2010), Roetter *et al.* (2007), Holden and Shiferaw (2004), and Kuyvenhoven *et al.* (1998). Akin to these bio-economic models, MP-MAS uses whole-farm mathematical programming, which captures human-environment interactions by updating the yield coefficients in the MP decision matrix, and has strengths in *ex ante* impact assessment. Yet, MP-MAS extends these conventional bio-economic models by implementing three major features: agent and landscape heterogeneity, spatial interactions, and social interactions.
First, it has been increasingly realized that the distributional effect of change is as important as its quantity and direction. Climate change, technology diffusion and agricultural policies such as conservation payments create winners as well as losers (e.g. Reidsma et al. 2010, Happe et al. 2009, Henseler et al. 2009). Whereas conventional bio-economic models are based on a limited number of representative farms (usually four or five) MP-MAS captures more diversity in economic and biophysical conditions by individually representing all plots and all farms.

Second, by representing the spatial aspects of agricultural production, MP-MAS allows for a coupling of decision models with spatially-explicit biophysical models, such as hydrological models of water flows and biophysical models of soil erosion. This is not possible with conventional bio-economic models, as they do not fully cover the spatial set-up of a landscape, creating only sketchy land use maps.

Third, by representing farm households individually, direct interactions between households can be modeled. This may include information sharing about new technologies, as well as the bilateral exchange of scarce resources (e.g. water and land) and certain forms of collective action (e.g. irrigation water use). Including these features in conventional bio-economic models requires iterative file-based procedures (see, for example Roebeling et al. 2000).

3 Description of the software

3.1 Purpose

The purpose of MP-MAS 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 modeling approach employs a scenario-based analysis to explore the impact of these changes.
The software is complex as the resource decisions and decision outcomes of each model agent depend on the quality of its resources, which is endogenous, as well as on the decisions of other model agents. MP-MAS is particularly suited to simulate empirical situations in which (a) there is upstream/downstream competition for irrigation water; (b) there is resource degradation such as soil fertility depletion; or (c) new technologies are introduced into the system.

Scientists are the main target users of MP-MAS as the parameterization and validation requires a strong background in mathematical programming and statistics. Resource managers, such as watershed managers and extension officers, can use a calibrated version with a Visual Basic front-end to test new management scenarios (Latynskiy et al. 2010).

3.2 State variables and scales

Within the agent-based component, the MAS has four hierarchical levels:

- **Agents** represent farm households, with as many agents modeled as there are farm households in reality. State variables of the agents include the location of the agents’ farmsteads, the location of their fields, the individual household composition (age, sex, and labor supply), available resources such as cash, livestock, tree orchards, farm equipment, and certain agent characteristics (e.g. membership in a population cluster and in an innovation segment).

- **Population clusters** are groups of agents with similar resource endowments used for the initialization of the agent-based model component (see initialization below).

- **Innovation segments** represent groups of agents with similar communication behavior when adopting innovations on their farms. Agents in the most innovative segment consider innovations in their decision-making right after introduction, while agents in the less innovative segments postpone deciding about innovation until many of their peers have
already adopted, i.e. sufficient information contagion has taken place. Early adopters thereby create a positive, frequency-dependent externality that lowers the hurdles for innovation for late adopters.

- *Populations* reflect social communication boundaries. Agents only interact with other agents in the same population.

Within the cellular component, the MAS has two hierarchical levels:

- *Pixels* represent the smallest landscape unit. The size of a pixel depends on the spatial resolution of the biophysical modules used in MP-MAS. The pixel size should ideally be set to the smallest observed field size in order to represent each field in the MAS. Multiple pixels can represent larger fields. State variables depend on the biophysical modules used and can include separate soil nutrients, organic matter, slope, slope length, and location in the hydrological system.

- *Soil types* are groups of pixels with similar soil fertility. The agent decision module refers to these groups as agents expect the same average crop yield for all pixels within one soil type. This reflects the empirical fact that farmers do not have perfect information about the state of each small landscape unit.

MP-MAS can be parameterized at various spatial scales, ranging from a village community to a large region within a country, depending on model purpose and data availability. If including hydrological processes then the spatial extent is usually a watershed or river basin.

### 3.3 Process overview and scheduling

The MAS proceeds in annual time steps. Within each time step, the agent decision module goes through three phases of investment, production, and consumption as shown in Figure 1. The
The biophysical module is executed between the production and the consumption phase and can follow any phases from daily to annual, depending on the particular biophysical features used.

**Figure 1**: Human-environment interaction in MP-MAS

Investment refers to the acquisition of assets such as land, equipment, or the planting of perennial crops that give returns beyond the current year. Investment decisions are therefore based on long-term expected yields and prices, and on expected future resource supplies. After investing, cash and asset endowments of each agent are updated. Although the MAS proceeds at annual time steps, seasonal or monthly constraints in the labor supply or water availability are taken into account by specifying these as constraints in the agent decision module.
The agent subsequently allocates its available resources to production in the current time step, according to the actual resource supply, as well as short-term expected prices and yields. Actual crop yields are then simulated for each plot from the production decision (crop choice, variable input level) and the resource condition (which, is optionally, affected by investments in livestock, soil, or water conservation). Finally, based on the actual simulated crop yields, the MAS calculates the agent household revenue. Part of the revenue is consumed or used to repay debts, and the remainder is added to savings that can be used for investment or production in the next time step.

At each time step, the age of farm equipment, livestock, and orchards is updated. Using an optional demographic module, also the age of individual household members can be updated. When using this module, each sex and each age has a pre-defined probability to give birth or to die. At each time step, the demographic module uses these probabilities to update the household composition and recalculate the labor supply. In the current model version, neither the change in family composition nor the founding of new households are endogenous agent decisions. As a consequence the number of households can decline over the simulation period, and their plots remain idle. Work is ongoing to implement the founding of new households and the reallocation of land in MP-MAS. For now, the demographic module should only be used for relatively short simulation periods.

3.4 Design concepts

*Emergence*: The diffusion path of an innovation (speed and saturation rate) emerges from the innovativeness of agents, the relative profitability of the innovation, and the frequency-dependent information contagion across agent segments. Land use patterns emerge in response to
changes in the relative scarcity of resources. Water flows result from water distribution in and abstraction from irrigation canals.

**Adaptation:** Agents can adjust their resource use (land, labor, water, cash, and livestock) in response to changes in the relative scarcity of these resources as affected by policies, climate, technologies, and markets. For instance, if the water supply declines then agents can switch to crops that use less water (*e.g.* grow soybean instead of rice) or adopt new technologies that save water (*e.g.* apply drip irrigation instead of sprinkler irrigation).

**Objectives:** Agents maximize their expected net farm and non-farm income while, optionally, satisfying their households’ consumption needs. For investment decisions, agents maximize their expected long-term average levels of net farm and non-farm income, while for production and consumption decisions they optimize current short-term levels.

**Prediction:** Agents form expectations about crop yields, water supply and market prices based on past experience, following the theory of adaptive expectations. Agents revise their expectations for a crop activity *j* periodically in proportion to the difference between actual (*Y*\(_{jt-1}\)) and expected values (*Y*\(_{jt}^*\)), as follows:

\[
Y_{jt}^* = Y_{jt}^* + \lambda \left( Y_{jt-1} - Y_{jt-1}^* \right), \quad 0 < \lambda \leq 1
\]  

(1)

in which \(\lambda\) is the coefficient of expectations. If \(\lambda=0\) then previous prices are expected to persist (static expectations). If \(0<\lambda<1\) then agents make proportional (downward or upward) adjustments to their expectations.\(^2\)

**Agent-agent interaction:** MP-MAS contains three options for including interactions between agents: local land markets, local water markets, and technology diffusion. Agents transact land

\(^2\) This is the basic functional form used for applications with only little inter-annual variability. In our most recent applications to semi-arid climates in Ghana and Chile we use more elaborate functional forms with 3 to 5 years weighted averages.
and water rights through an auction mechanism based on shadow prices. If an agent's shadow price for a resource is below the average price then the agent will attempt to rent out a unit of the resource; otherwise it will try to acquire a unit by placing a bid in the auction. The resource is temporarily exchanged with the highest bidding agent for an amount of rent. The auction considers internal transport costs, which favors resource exchanges among neighboring agents. Agent interactions in technology diffusion were implemented as frequency-dependent contagion effect; the more agents adopt a technology, the more it becomes accessible to others.

Agent-environment interaction: Crop yields in the MAS capture the two-way interaction between farm decision-making and agro-ecology (Figure 1). For MP-MAS applications that simulate water flows, crop yields are a function of the water supply, irrigation method, and water-unconstrained yield potential that captures land quality factors constant during the simulation. For MP-MAS applications with soil nutrient flows incorporated, crop yields are a function of the nutrient-unconstrained yield potential, management decisions and available soil nutrients. Agent decisions also have a direct impact on resource dynamics, through crop choice, investments in irrigation infrastructure and the use of fertilizers, but it is only through impacts on crop yields and irrigation water that agents receive feedback about changes in resource conditions. Agents learn about environmental changes through a reduction in crop yields, which creates an incentive to adjust crop choice and input levels, or to adopt soil and water conservation methods.

Stochasticity: Random numbers can be used for initializing the MAS if empirical data are incomplete to parameterize all state variables individually for each agent (see next section). If the MAS includes rainfall, then stochasticity is also used to simulate rainfall events from historical
weather data. If the MAS includes mortality and fertility of agent household members, random numbers are combined with empirical probabilities to simulate demographic change.

3.5 Initialization

Berger and Schreinemachers (2006) described the Monte Carlo method implemented in MP-MAS to generate alternative agent populations from a random sample of farm households. Following this method, agents are grouped into more homogeneous clusters, and probability distribution functions are quantified for each cluster and for each resource. A randomization procedure is then used to generate as many agents as there are farm households in the cluster. The method has been shown to take correlations between resources into account and to create agent populations with a close statistical fit to the actual farm population.

Spatial input data include a raster map indicating which pixel belongs to which agent. This map can be created from a farm survey, cadastral map, or randomly if empirical data are incomplete. Other spatial data depend on the biophysical component used.

3.6 Input

MP-MAS input data are organized by modules in a set of 14 Excel workbooks (or an SQL database, see Berger et al. 2010) listed in Table 1.

The generic MP matrix is organized in an Excel workbook called Matrix.xlsx. This workbook defines the structure of the MP matrix, the signs of the constraints, and contains all matrix coefficients that do not change during the simulation. Matrix can also be used as a stand-alone MP model that can be solved independently from the other input files using a spreadsheet solver. All other input files in MP-MAS, listed in Table 1, tailor the MP matrix to each agent’s decision space. Berger and Schreinemachers (2009) provided details about each module and input file.
The data requirements of MP-MAS depend on which modules are selected for an empirical application. At a minimum, it requires farm survey data to parameterize resource endowments and gross margins for all farm activities. It also requires spatial data on the location of farmsteads and agricultural fields as well as spatial data to differentiate fields into different qualities, such as slope, elevation, soil nutrients—depending on the application.
Table 1: MP-MAS input files and their function

<table>
<thead>
<tr>
<th>Input file</th>
<th>Explanation</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard modules</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. ScenarioManager</td>
<td>Defines the scenarios and converts Excel files to plain text input files</td>
<td>Scenario setup</td>
</tr>
<tr>
<td>2. Basic Data</td>
<td>Contains basic parameters used in several modules of the software (<em>e.g.</em> pixel size)</td>
<td>Model parameters</td>
</tr>
<tr>
<td>3. Matrix</td>
<td>Defines the structure and coefficients of the mathematical programming matrix</td>
<td>To simulate the decision-making</td>
</tr>
<tr>
<td>4. Population</td>
<td>Basic characteristics of the agent populations: <em>e.g.</em> members, assets, access to technologies</td>
<td>Defines the initial characteristics of the agents</td>
</tr>
<tr>
<td>5. Map</td>
<td>All spatial information including the location of agents and plots, land quality and water flows</td>
<td></td>
</tr>
<tr>
<td>6. Network</td>
<td>Defines the characteristics of innovation networks and specifies technical details of all innovations</td>
<td></td>
</tr>
<tr>
<td>7. Demography</td>
<td>Specifies the available labor hours and, optionally, fertility and mortality rates and food requirements</td>
<td>Define the changes over time (<em>e.g.</em>, human ageing, tree and livestock growth, price changes)</td>
</tr>
<tr>
<td>8. Market</td>
<td>Market prices of purchased inputs and farm outputs. Optionally specifies parameters of expenditure models</td>
<td></td>
</tr>
<tr>
<td><strong>Optional modules</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Perennials</td>
<td>Input and output of perennial crops by type and age</td>
<td></td>
</tr>
<tr>
<td>10. Livestock</td>
<td>Input and output of farm animals by species, age, and sex</td>
<td></td>
</tr>
<tr>
<td>11. Soils</td>
<td>Parameters of the Tropical Soil Productivity Calculator or coupling data for external software (<em>e.g.</em> LUCIA)</td>
<td></td>
</tr>
<tr>
<td>12. Routing</td>
<td>Precipitation levels and the distribution of surface and sub-surface water flows</td>
<td></td>
</tr>
<tr>
<td>13. Water Rights</td>
<td>Agents’ access to water sources for irrigation</td>
<td></td>
</tr>
<tr>
<td>14. CropWat</td>
<td>Specifies crop yields as a function of crop water supply</td>
<td></td>
</tr>
</tbody>
</table>
3.7 Submodels

Agent decision module: At the core of the MAS is the MP matrix that simulates the decision-making of individual farm households by repeatedly solving a constrained optimization problem. MP-MAS uses recursive MP as it tailors the matrix to each agent by updating at each time step its resources, such as land, labor, cash and machinery, as well as its expectations about water, crop yields, and market prices. MP-MAS uses optimization in a descriptive ("positive") and not in a prescriptive ("normative") way. The optimization routine simulates the actual decisions of farm households; it does not prescribe individual farmers how to produce more with the same resources.

Following Hazell and Norton (1986: 11), the general optimization (or MP) problem is formulated as:

$$\max Z = \sum_{j=1}^{n} c_j X_j$$  \hspace{1cm} (2)

Subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i \quad \text{all } i = 1 \text{ to } m$$ \hspace{1cm} (3)

$$X_j \geq 0 \quad \text{all } j = 1 \text{ to } n$$ \hspace{1cm} (4)

In which the farm household objective $Z$ is a linear function of the alternative farm activities $X_j$ ($j=1$ to $n$), such as growing crops, raising livestock, hiring labor, consuming food, and adopting new technologies, and the expected returns per unit of the activity $c_j$. Depending on the empirical situation, the function $Z$ can be defined in MP-MAS as expected net farm income, net household income, or a multi-dimensional utility function that includes income and consumption. The optimization algorithm will find values of $X_j$ that give the highest value for $Z$ without violating...
the resource constraints (Eq. 3) or involving negative activity levels (Eq. 4). The technical coefficients \( a_{ij} \) in Eq. 3 are the quantities of an available resource \( b_i \) required to produce one unit of an activity \( X_j \); for instance, man-days of labor to cultivate one hectare of rice. These technical coefficients can be derived from empirical production functions, estimated using field experiment data or farm survey data. Resource constraints can include hard constraints (land, labor supply, and cash) as well as soft constraints (limited information and market access). They can also include minimum consumption requirements to capture the fact that in some empirical settings farm households give, for instance, greater priority to fulfill their own rice consumption needs than to sell cash crops to the market. The inclusion of soft constraints creates a fissure between the actual farm decisions and the economic optimum decisions. The use of adaptive expectations—using expected rather than actual values for crop yields, water supply and market prices—creates an additional such fissure.

**Technology diffusion (optional module):** Technology diffusion in MP-MAS follows a two-stage process. The first stage includes a frequency-dependent contagion effect. Agents are grouped into five innovation segments reflecting their willingness or ability to adopt new technologies (that is, their innovativeness). Only when agents in the higher segment of innovativeness have adopted, does the technology become accessible to agents in the lower segment. Once accessible, the technology is inserted as one activity in the specific MP matrix of the agent. Solving all MP matrices for all agents then simulates the sequence of adoption decisions and the emerging innovation diffusion. Membership to innovation segments can be empirically estimated from social network analysis (for more details see Berger 2001 and Schreinemachers et al. 2009).

**Land and water markets (optional):** Transactions between agents regarding land and water rights are based on shadow prices and distance costs. For instance, the shadow price of land is the
amount the MP objective value (usually the expected household income) would increase if one more unit of land was available. This shadow price minus a distance cost, which captures transportation to and from the plot, represents the agent’s willingness to pay for an additional unit of land.

**Livestock (optional):** The input data specify input requirements (*e.g.* labor, feed, pasture area, cash) and output quantities (*e.g.* milk, meat, eggs, offspring, manure) per head for each animal species and for each age in its lifespan. The choice of animal species as well as the number and type of inputs and outputs is flexible. At each time step, these values are updated in the agent’s MP matrix, according to an individual-based livestock herd model. Agents then decide whether to maintain or sell the animal.

**Perennial crops (optional):** Similar to livestock, the input data also specify the input requirements (labor, cash, and water) and output quantities per hectare of perennial crops (*e.g.* apple trees, coffee, roses) for each time step in their lifespan. Different from livestock, the current version of MP-MAS does not allow agents to cut their perennial crops, which are assumed to last till the end of their pre-defined lifespan. Agents can, however, switch management practices and change the input intensity and yields in their orchards.

**Biophysical modules (optional):** MP-MAS simulates resource dynamics and crop yields, either utilizing built-in features or using external software. The decision-making module interacts with the biophysical module in the following way: First, the decision-making module simulates land use based on expected conditions (soil, water, prices). The simulated land use is translated to a raster map and is transferred to the biophysical module, which then simulates the actual resource conditions and calculates the actual crop yield in each pixel. Finally, the actual crop yield (and
optionally, the actual water supply) is transferred back to the agent decision module where it is evaluated and used to update the yield expectations and, optionally, water expectations.

Two types of resource dynamics are currently incorporated in MP-MAS, one related to water flows, the other related to soil erosion and soil nutrients. For each of these there are empirical and process-based implementations available. Empirical here means that biophysical processes in soils and plants are not made explicit, but are approximated by fitting functions to observed data.

First, the EDIC (spanish acronym of Civil Engineering Consortium in Chile) simulation model is an empirical model of irrigation water flows using a node-link network (for parameters and equations, see Arnold 2010). The landscape is divided into irrigation sectors that receive water from streams (surface flows) and sub-surface flows. Fitted parameters, defined in the input data, determine the proportion of the inflows used for irrigation in each sector. The EDIC model considers the irrigation return-flows, i.e. seepage, bypass and tailwater flows, that can be reused further downstream. Since return-flows result from the actions of upstream water users, this particular feature constitutes one important agent-environment interaction. The input data also defines the total volume of river flow and precipitation on a monthly basis.

Second, WASIM-ETH (Water balance Simulation Model ETH-Zürich) is a process-based hydrology model developed by Jasper et al. (2002) to capture water flows at high spatial and temporal resolutions. The model contains features such as a set of evaporation algorithms, an interception module, a layered soil module based on the Richards equation, a multi-layer groundwater module, and a glacier module (Schulla and Jasper 2007). WASIM-ETH can be coupled to MP-MAS as an external software component, using the Typed-Data-Transfer (TDT) library of Linstead (2004) (see details in Arnold et al. 2008). To capture irrigation flows with
relatively low on-field irrigation efficiencies, we extended the original WASIM-ETH source code as explained in Uribe et al. (2009).

Both EDIC and WASIM-ETH determine the water supply to each irrigation sector in the landscape. A predefined set of agent water rights then determines the actual distribution of water among agents and plots in each sector. Here there are three options available in MP-MAS: (i) all agents have equal access to water, (ii) all plots have equal water supply, or (iii) empirical water distribution rules (for example, based on the actual water rights registry of water user associations). As an optional feature, agents can trade water rights amongst themselves. The crop yield is a function of the deficit between the crop water supply and the crop water requirement, as based on the FAO56 (also called CropWat) model (Allen et al. 1998). The MAS simulates the actual yield by multiplying the water-unconstrained yield potential with a reduction factor. The input data specify the crop water requirements and irrigation methods.

Third, the Tropical Soil Productivity Calculator (TSPC) is an empirical model of soil fertility changes and resulting crop yields (Aune and Lal 1995). Schreinemachers (2006) specified the model equations separating nutrient stocks and available nutrients for plants. TSPC simulates crop yields by multiplying the crop yield potential with a reduction factor, if available nutrients (N, P, and K), acidity and soil organic matter are below their optimum levels. Available nutrients are a function of initial soil conditions, harvest removal, erosion and leaching, decomposition of organic matter, and management decisions.

Fourth, the Land Use Change Impact Assessment (LUCIA) model is a raster-based, spatially-explicit dynamic model that simulates watershed functions, soil fertility and plant growth for small catchment areas up to about 30 km\(^2\) (Marohn et al. 2010). LUCIA has hydrological functions that describe the flows and stocks within each pixel, while flows between pixels are
routed according to a local drain direction map. Biomass production in LUCIA follows a hierarchical approach in which the potential growth—determined by radiation, temperature, leaf area index, and development-dependent maximum assimilation—is first reduced by the water supply and then by N, P, and K availability based on CGMS-WOFOST (Supit 2003). LUCIA can be coupled to MP-MAS as an external software component using the TDT library.

Fifth, EXPERT-N is a process-based model system to simulate crop growth in arable farming. It builds on state-of-the-art crop growth models such as CERES, SPASS, SUCROS, and GECROS, and contains various modules for soil water flow, soil heat transfer, soil carbon and nitrogen turnover, and other soil-plant-atmosphere processes on a daily basis (Priesack et al. 2001, 2006). Like WASIM-ETH and LUCIA, EXPERT-N can be coupled with MP-MAS as an external software component using the TDT library (Berger et al. 2010).

4 Modeling choices in MP-MAS

4.1 Empirical applications

MP-MAS has been applied to various research questions related to the impact of policy changes and the introduction of agricultural innovations, as listed in Table 2, with studies located in six countries: Chile, Germany, Ghana, Thailand, Uganda and Vietnam. The applications to Germany, Thailand, and Uganda have detailed associated documentation which can be downloaded from the software website (see first page).
Table 2: Research questions addressed in MP-MAS applications

<table>
<thead>
<tr>
<th>Country</th>
<th>Location of site</th>
<th>Research question</th>
<th>Key references</th>
<th>Project period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chile</td>
<td>Maule river basin</td>
<td>What would be the impact of water pricing on the efficiency of irrigation water use and land use dynamics?</td>
<td>Berger et al. 2007, Berger 2001</td>
<td>2004-2009</td>
</tr>
<tr>
<td>Germany</td>
<td>Swabian Jura, southwest Germany</td>
<td>What could be the impact of climate change on land use and farm incomes?</td>
<td>Berger et al. 2010</td>
<td>2009-2011</td>
</tr>
<tr>
<td>Ghana</td>
<td>White Volta basin</td>
<td>What would be the impact of a transition from rain fed to irrigated agriculture?</td>
<td>Birner et al. 2010</td>
<td>2004-2009</td>
</tr>
<tr>
<td>Thailand</td>
<td>Chiang Mai Province in the mountainous north</td>
<td>What would be the impact of four fruit tree technologies (fruit drying, artificial flower induction, extended shelf-life, and improved irrigation) on land use, erosion and levels of pesticide use?</td>
<td>Schreinemachers et al. 2010, 2009</td>
<td>2006-2012</td>
</tr>
<tr>
<td>Uganda</td>
<td>Lake Victoria crescent in the southeast</td>
<td>What would be the impact of hybrid maize varieties and better access to farm credit on poverty and environmental sustainability?</td>
<td>Schreinemachers et al. 2007, Schreinemachers 2006</td>
<td>2001-2006</td>
</tr>
<tr>
<td>Vietnam</td>
<td>Son La Province in the country’s mountainous north</td>
<td>How would the adoption of soil conservation measures affect short- and long-term household incomes?</td>
<td>Quang et al. 2010</td>
<td>2006-2012</td>
</tr>
</tbody>
</table>

Table 3 shows that MP-MAS can be applied to a variety of spatial extents and human population sizes. In large research interdisciplinary research projects, the spatial extent is often based on natural boundaries such as river basins or watersheds (the Chile, Ghana, Thailand, and Vietnam applications). Given availability of empirical data, MP-MAS can use any spatial extent or population size and can therefore adjust itself to the spatial extent of the biophysical modules selected. The application to a catchment area in Vietnam had a spatial extent of about 6 km², while the application to a river basin in Chile covered 5,300 km². The number of households individually represented in MP-MAS ranged from 471 in Vietnam to 34,691 in Ghana. Also the pixel size can vary between applications, but should ideally be set to the smallest observed field size to make sure that every field is represented in the MAS.
Table 3: Scale of landscape and agent representation in MP-MAS

<table>
<thead>
<tr>
<th>Model component</th>
<th>Chile</th>
<th>Germany</th>
<th>Ghana</th>
<th>Thailand</th>
<th>Uganda</th>
<th>Vietnam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of study area</td>
<td>Watershed</td>
<td>Landscape</td>
<td>Watershed</td>
<td>Watershed</td>
<td>Two villages</td>
<td>Catchment</td>
</tr>
<tr>
<td><strong>Landscape</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixels</td>
<td>530,000</td>
<td>129,758</td>
<td>377,900</td>
<td>8,542</td>
<td>2,258</td>
<td>61,965</td>
</tr>
<tr>
<td>Pixel size (m)</td>
<td>100x100</td>
<td>100x100</td>
<td>100x100</td>
<td>40x40</td>
<td>71x71</td>
<td>10x10</td>
</tr>
<tr>
<td>Agricultural area (km²)</td>
<td>5,300</td>
<td>1,297</td>
<td>3,779</td>
<td>13.67</td>
<td>11.38</td>
<td>6.20</td>
</tr>
<tr>
<td><strong>Agents</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>3,592</td>
<td>1,700</td>
<td>34,691</td>
<td>1,309</td>
<td>520</td>
<td>471</td>
</tr>
<tr>
<td>Sampling fraction</td>
<td>1.0*</td>
<td>1.0*</td>
<td>0.004</td>
<td>0.23</td>
<td>0.23</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Note: * Based on census data and therefore the sampling fraction is 1.0.

Generally, both water and soil conditions determine crop yields but, as Table 4 shows, most applications either represented hydrology processes or soil processes in MP-MAS. The identification of the most constraining factor to crop yields mainly determines this selection. The exception is the coupling to LUCIA, which simulates both hydrology and soil dynamics. It would also be possible in MP-MAS to combine FAO56 + EDIC + TSPC.

The choice between empirical biophysical models (EDIC, TSPC) vs. process-based biophysical models (WASIM-ETH, LUCIA, EXPERT-N) largely follows from the organization of the project and its research objectives. Soil and plant scientists in large multi-disciplinary teams usually prefer working with state-of-the-art biophysical models and can hardly be convinced of using simple empirical models. This is especially the case when the project seeks to find new insights into the agricultural system, which can only be obtained by inclusion of detailed biophysical processes. In small teams or individual PhD projects, however, selecting process-based biophysical models is clearly out of scope.

Table 4: Main differences between the MP-MAS applications
<table>
<thead>
<tr>
<th>Model feature</th>
<th>Chile</th>
<th>Germany</th>
<th>Ghana</th>
<th>Thailand</th>
<th>Uganda</th>
<th>Vietnam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crop-soil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSPC</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td>EXPERT-N</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td><strong>Crop-hydrology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAO56 + EDIC</td>
<td>☑️</td>
<td>☐</td>
<td>☑️</td>
<td>☑️</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>FAO56 + WASIM-ETH</td>
<td>☑️</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td><strong>Crop-soil-hydrology</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUCIA</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
</tr>
<tr>
<td><strong>Optional modules</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perennial crop production</td>
<td>☑️</td>
<td>☐</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td>Livestock production</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td>Out-migration</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td>Expenditure model (LA-AIDS)</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
</tr>
<tr>
<td>Fertility &amp; mortality (pop. growth)</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td><strong>Agent-interactions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endogenous commodity prices</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Endogenous land markets</td>
<td>☑️</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Endogenous water markets</td>
<td>☑️</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Innovation diffusion in networks</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td><strong>Agent objectives</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected net cash income</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
<td>☑️</td>
</tr>
<tr>
<td>Exp. consumption of own farm produce</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
<td>☑️</td>
<td>☐</td>
</tr>
<tr>
<td>Minimum food requirements</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☑️</td>
</tr>
<tr>
<td><strong>Size of the decision component</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of activities in MP</td>
<td>1,119</td>
<td>1,280</td>
<td>752</td>
<td>1,820</td>
<td>2,350</td>
<td>941</td>
</tr>
<tr>
<td>Number of constraints in MP</td>
<td>224</td>
<td>879</td>
<td>250</td>
<td>812</td>
<td>560</td>
<td>488</td>
</tr>
<tr>
<td>Number of integers in MP</td>
<td>27</td>
<td>23</td>
<td>60</td>
<td>73</td>
<td>50</td>
<td>43</td>
</tr>
</tbody>
</table>
Each study tailored MP-MAS to a different agricultural system by specifying livestock, crops, crop combinations, and crop constraints in the MP matrix, and by selecting the relevant model features. Table 4 shows for each application which modules were selected. The empirical setting, the objectives of the research, and the particular project set-up determined each selection. For instance, land transactions are only included if this is frequent in reality, and population growth is only included if there is evidence that this is a driver of land use change.

Table 4 also shows the size of the MP matrix. The number of activities is generally large as there is one separate activity for each combination of crops, input levels, and land quality. The Uganda application, for instance, included 11 crops and 7 intercrop combinations, each segmented into 90 activities by specifying different combinations of land quality, labor, and fertilizers (Schreinemachers et al. 2007). Technical coefficients were derived from regression functions, and the non-linear response of crop yields to alternative combinations of inputs was captured using a piecewise linear segmentation.

4.2 Selected results related to technology assessment

In the study of the Maule river basin in Chile, Berger (2001) showed that the impacts of new technologies crucially depend on the type of technology diffusion and the adoption cost this involves. Berger compared two scenarios. In one scenario, the agents had equal and immediate access to all technologies, while in the other technologies were diffused through a frequency-dependent contagion effect. He found that the latter scenario created significantly more structural change in farm sizes and land use patterns: early adopters gained higher profits, which increased the amount adopters would pay non-adopters for their land, and led to more land transactions from non-adopters to adopters.
Schreinemachers et al. (2007) assessed the impact of better access to short-term credit, improved maize varieties, and mineral fertilizer both on soil fertility and poverty distribution in two Ugandan villages (Figure 2). They found that improved access was able to reduce poverty by 20 percent, as 31 percent of the agents moved from below to above the poverty line, which was expressed in terms of calorific intake in the agent households. The ecological sustainability of the system was, however, not improved as inorganic fertilizers did not yield long-run benefits in terms of soil fertility.

Figure 2: Distributional effect of improved access to credit and technologies in a Ugandan village

Note: Simulated poverty levels for 520 agents in two scenarios averaged over 15 years. Poverty line is 3.3 billion joules per capita (in male adult equivalents) per year.

In a study to a watershed in northern Thailand, Schreinemachers et al. (2009) compared the diffusion of greenhouse agriculture for farmers with and without transferable land titles that can be used as mortgage collateral. They found that if mortgage collateral would not be required,
then diffusion among farmers without titles could reach nearly 77% by 2020, as compared to about 36% under current conditions (Figure 3).

Figure 3: Diffusion of greenhouse agriculture in a northern Thai watershed, 1995-2020

Note: Graph shows observed values for 1995-2006 and simulated values for 2007-2020.

The results show the importance of capturing agent heterogeneity when simulating technology adoption in agricultural systems. Due to the heterogeneity of resources, technologies are not equally attractive to all farm households; and further, because of the heterogeneity in terms of innovativeness, the benefits of adoption are spread unequally. The combination of these two factors creates an intricate pattern of technology diffusion, resource use, and environmental externalities that these software applications are capable of capturing.

4.3 Model validation tests

McCarl and Apland (1986) separated between ‘validation by construct’ and ‘validation by results’. In MP-MAS, validation by construct is tackled by building the MAS on well-established theories in farm economics and agro-ecology. Production and expenditure functions have a solid
footing in economic theory, and validity of their functional parameters can be judged from their signs, their significance levels, and the predictive power of the function as a whole.

Validation by results is achieved by studying the baseline scenario, which reflects the current situation and current processes without additional interventions. As a minimum requirement, all applications of MP-MAS compared the observed land use with the simulated land use. Spatial validation methods have so far not been used with MP-MAS as all applications have studied land use at a household or population level and none have looked at the spatial patterns of land use change. In the following we highlight the validation methods used in the Uganda and Thailand studies.

The Ugandan study validated the baseline in three ways. It first compared the simulated soil nutrient balances to secondary data from literature and found the model predictions to be within the range of what other studies had suggested. Second, the study regressed the observed land use (as a percentage of the total crop area) on the simulated land use averaged over the first three years of the simulation run and found a sufficient goodness-of-fit. Third, it compared the simulated distribution in poverty levels with the actual distribution from survey data and also found a close resemblance between these distributions.

The Thailand study solely relied on regression of observed land use on simulated land use but did so at five levels of aggregation from the watershed to the individual household level. It showed a good fit at the watershed level, a sufficient fit at the cluster level, and a moderate fit at the household level. This suggests that MP-MAS was not able to replicate the individual land use decisions of each real-world household, but at higher levels of aggregation (agent clusters, innovation segments) it was a sufficiently good statistical representation of reality.

4.4 Treatment of uncertainty
The Monte Carlo initialization of MP-MAS generates many possible and statistically consistent agent populations that can then be used for repetitions of simulation experiments. For example, Schreinemachers et al. (2010) allocated agents randomly to innovation segments to study the diffusion of tree crop technologies in northern Thailand; they ran the scenario ten times and then depicted the diffusion curves using confidence intervals.

Comparing impacts from different policy interventions requires some form of uncertainty analysis. We explain our approach by referring to the Ugandan case study in Berger and Schreinemachers (2006). As shown in Figure 4, we tested the sensitivity of simulation outcomes for key policy indicators such as crop yield, productivity, and farm income. Variation of these indicators was measured by standard deviations (expressed as percentages of the normalized mean) in fifty different agent populations for the baseline scenario.

Figure 4: Model uncertainty for key policy indicators in Uganda

Note: Variation results from fifty different agent populations for the baseline scenario. Variation is measured by standard deviations (expressed as percentages of the normalized mean).
The sensitivity tests revealed rather low variation for most key policy indicators in the order of 5%; only in the case of farm assets including savings variation was in the order of 10%. This inherent model “noise” (or uncertainty) has to be considered when comparing various simulation experiments, for example on policy interventions in markets for credit and fertilizers. Only in case that the policy indicators differ by more than this “noise”, interventions should be interpreted as having significant impact. More details on uncertainty and sensitivity testing can be found in Schreinemachers (2006).

5 Comparison to other recent simulators

In this section we briefly compare MP-MAS to eight other agent- and non-agent-based software packages that simulate human-environment interactions in agricultural systems. The purpose is to compare decision routines, biophysical dynamics, and the interactions between them as well as the way these features are implemented in the various software packages. We will not try to judge model and software quality, which is impossible, as the modeling approaches represent different agricultural systems, have different purposes and cover different spatial extents.

5.1 Selected simulators for comparison

Table 5 lists the simulators in our comparison and summarizes their objectives and application areas; the footnote to the table cites the articles that the comparison was based on. Two criteria were used in selecting the candidates for comparison. The first criterion was that the decision-making and the biophysical dynamics were both endogenous and interact with each other. Simulation models such as DSSAT (Jones et al. 2003), APSIM (Keating et al. 2003), SWAT (Arnold et al. 1998), and many others, also simulate environmental processes and include a
management component, but do not simulate decision-making endogenously. We also have not included agricultural systems models such as AgriPolis (Happe *et al.* 2006) or LUPAS (Roetter *et al.* 2007, 2005), which incorporate endogenous land use decisions, but do not have endogenous biophysical dynamics that react to the land use decisions.

The second criterion was that these software packages simulated the *actual* decision-making of farm households. We therefore excluded all types of optimal control models that give a prescriptive (“normative”) assessment on how to optimize decision-making. All simulators selected are descriptive (“positive”) models and use some form of adaptive expectation formation, which captures the fact that real-world decision-makers cannot predict crop yields with certainty.
Table 5: Basic information the eight simulators used in the comparison

<table>
<thead>
<tr>
<th>Software</th>
<th>Study area</th>
<th>Agricultural system</th>
<th>Purpose of the study (broadly defined)</th>
<th>Decision-making</th>
<th>Resource dynamics</th>
<th>Crop yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ABSTRACT</td>
<td>One river basin in northeastern Brazil (~74,000 km²)</td>
<td>Commercial agriculture, semi-arid, with upstream and downstream water users</td>
<td>To analyze the dynamics of water use for irrigation and its effect on the distribution of water resources</td>
<td>Heuristics (agent-based) with random elements for crop choice. Separate heuristics for upstream, floodplain, and downstream agents</td>
<td>Semi-distributed water balance model (node-link-network) and a hydraulic model to regulate water flows on 10 day interval</td>
<td>Crop growth simulated on 10-day interval as a function of water stress based on CATCHCROP</td>
</tr>
<tr>
<td>2. CATCHSCAPE³</td>
<td>One sub-catchment in north Thailand (~44 km²)</td>
<td>Semi-commercial with upstream and downstream water users and forest use</td>
<td>To facilitate the negotiation between stakeholders about the sustainable use of water resources</td>
<td>Constrained optimization (agent-based) combined with heuristics for rice planting and off-farm labor.</td>
<td>Same as ABSTRACT</td>
<td>Same as ABSTRACT</td>
</tr>
<tr>
<td>3. IMT²</td>
<td>One sub-catchment in north Thailand (~44 km²)²</td>
<td>Semi-commercial agriculture on sloping land (rice, sorghum, groundnut)</td>
<td>To assist stakeholders in their land-use planning at a catchment level</td>
<td>Constrained optimization (representative farm approach) of expected annual income, using three farms for the study area</td>
<td>Rainfall-runoff model (IHACRES), a water allocation model based on stakeholder recommendations, and an erosion model (USLE)</td>
<td>Crop growth (10-day time step) function of temperature, water supply, soils, and fertilizer use as based on CATCHCROP</td>
</tr>
<tr>
<td>4. SIM</td>
<td>Two states in northeastern Brazil (~400,000 km²)</td>
<td>Commercial agriculture under semi-arid conditions</td>
<td>To assess the impact of climate change on natural resources and to identify possible coping strategies</td>
<td>Constrained optimization of farm income to simulate land use decisions at municipality level (~1200 km²)</td>
<td>Regional-level models for climate change scenarios, water balance, and water use</td>
<td>Crop yields function of water and aeration stress, incl. variations in soil quality and management</td>
</tr>
</tbody>
</table>
### B. Software for simulating soil fertility dynamics

<table>
<thead>
<tr>
<th>Software ¹</th>
<th>Study area</th>
<th>Agricultural system</th>
<th>Purpose of the study (broadly defined)</th>
<th>Decision-making</th>
<th>Resource dynamics</th>
<th>Crop yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. ECEC-MOD</td>
<td>Four regions in southern Norway (~989 km²)</td>
<td>Commercial agriculture (grains, grassland, livestock)</td>
<td>To estimate the effect of changes in economic incentives on emissions (N, P, and pesticides)</td>
<td><em>Constrained optimization (representative farm approach)</em> of expected profit</td>
<td>Models of hydrology, N and P dynamics, weeds, erosion and leaching, and ammonia losses</td>
<td>Crop yield is a function of N (from manure, mineral fertilizer, organic matter)</td>
</tr>
<tr>
<td>6. LUDAS</td>
<td>One watershed area in central Vietnam (~100 km²)</td>
<td>Subsistence agriculture at forest margins, including forest logging</td>
<td>To provide technical decision support for stakeholders in land use planning</td>
<td><em>Heuristics (agent-based)</em> combined with random elements</td>
<td>Natural vegetation growth using rule-based transitions in land cover. A growth equation simulates the forest stand basal area</td>
<td>Crop yield is a function of input and labor use, physical soil characteristics and land use history based on regression model</td>
</tr>
<tr>
<td>7. PALM</td>
<td>Mid-hills of Nepal (~0.98 km²)</td>
<td>Semi-subsistence agriculture on sloping land susceptible to degradation</td>
<td>To evaluate the potential of various soil fertility enhancing innovations and the likelihood of their adoption</td>
<td><em>Heuristics (agent-based)</em> combined with mimicking behavior for 98 agents</td>
<td>CENTURY model of organic matter decomposition ⁵. Water and N dynamics based on DSSAT family of models ⁶</td>
<td>Crop growth (1-day time step) function of climate, soils, and input use with separate models for crops, trees and weeds</td>
</tr>
<tr>
<td>8. SAM</td>
<td>South-western Saskatchewan, Canada (~1.364 km²)</td>
<td>Commercial agriculture (wheat, canola, pea, forage, and native vegetation)</td>
<td>To evaluate the agro-ecosystem sustainability of agricultural production systems</td>
<td><em>Constrained optimization of profit with rules for fertilizer use (N and P) to simulate land use at the level of four “ecodistricts”</em></td>
<td>Model of soil water availability to crops, and models for available N and P</td>
<td>Crop yield a function of climate and soil quality; the latter influenced by crop management in previous years</td>
</tr>
</tbody>
</table>

Notes: ¹ Some software packages include additional components not listed here. The comparison was based on the following references: CATCHSCAPE: Becu et al. 2003; ABSTRACT (Agent-based Simulation Tool for Resource Allocation in a Catchment): van Oel et al. 2010; SIM (Semi-arid Integrated Model): Krol and Bronstert 2007; IMT (Integrated Modeling Toolbox): Letcher et al. 2006a, 2006b; SAM (Sustainable Agroecosystem Model): Belcher et al. 2004; PALM (People and Landscape Model): Matthews 2006; ECECMOD (Economics and Ecology Modeling System): Vatn et al. 1999, 2006; LUDAS (Land Use Dynamic Simulator): Le et al. 2008, 2010. ² Developed within the Integrated Water Resource Assessment and Management (IWRAM) project. ³ Based on the CORMAS platform (Bousquet et al. 1998) and is used for participatory simulation modeling with stakeholders. ⁴ CATCHSCAPE and IMT use the same study site (Mae Uam sub-catchment). ⁵ Parton et al., 1988; Parton and Rasmussen, 1994. ⁶ [http://www.icasa.net/dssat/](http://www.icasa.net/dssat/)
5.2 Decision-making

Figure 5 classifies the software packages according to the decision-making modules implemented. SAM and SIM do not model individual farm households but higher levels of aggregation (eco-districts and municipalities, respectively); both use constrained optimization to simulate land use decisions. ECECMOD and IMT also use constrained optimization but, similar to conventional bio-economic models described above, use a representative farm approach and do therefore not individually represent each real-world farm household. Of the agent-based simulation models, ABSTRACT, LUDAS and PALM use heuristics while MP-MAS and CATCHSCAPE use constrained optimization to simulate crop choice and management decisions, adding heuristics to capture additional decisions in the MAS. However, CATCHSCAPE uses a highly simplified MP matrix with most decisions modeled using heuristics. The comparison hence shows that MP-MAS distinguishes itself in its use of a detailed constrained optimization approach to represent the decision-making of each individual farm household. It is therefore the only agent-based software package with a strong footing in microeconomics and farm management theory.

Figure 5: Classification of decision-making components

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3 CATCHSCAPE actually represents only two-fifths of the real-world plots and farm households.
Of all simulators in our comparison only PALM and MP-MAS have modules for technology diffusion. Agents in PALM mimic each other if they see their immediate neighbors use a strategy that gives higher returns. This is different from MP-MAS, which combines communication network effects with an economic evaluation of technologies in which agents only adopt if they expect that adoption would contribute to reaching their individual household objectives.

5.3 Environmental dynamics

The conventional taxonomy for environmental models separates them into deterministic (process-based and statistical-based) and stochastic models. Integrated software packages, however, almost always combine all these features into a single modeling approach. As an alternative, we classify the various software packages in a first step based on the main type of biophysical process modeled (i.e., hydrology or soil dynamics), and in a second step based on their temporal resolution (Figure 6). We note that models with fine temporal resolution are mostly process-based while those using a coarse resolution are mostly empirical-based, relying on statistical relationships in the data.

Figure 6: Classification based on biophysical modules
Among the software packages simulating water flows, ABSTRACT, CATCHSCAPE, and ITM—all based on the CATCHCROP model (Perez et al. 2002)—include hydrological processes at a 10-day time step while SIM simulates water availability at a daily time step. This fine temporal resolution is comparable to the MP-MAS (+WASIM) specification while MP-MAS (+EDIC), on the other hand, uses a coarse resolution of monthly time steps and, unlike the other simulators, is not process-based. The option using the EDIC module is suitable if water availability is an important aspect of the system under study, yet hydrological data such as flow measurements are largely unavailable.

Among the software packages simulating soil fertility changes, we can also distinguish between simulators using a fine temporal resolution (ECECMOD, PALM, SAM, MP-MAS (+LUCIA or EXPERT N)), which are based on an advanced understanding of the biophysical processes in the soil-plant system, and those that rely on statistical correlation in the data (LUDAS, MP-MAS (+TSPC)).

The comparison hence shows 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.

5.4 Human-environment interactions

In all software packages, agents influence the environment through their land use and input decisions while the environment influences agents by returning a level of crop yield, which is a function of input decisions and environmental processes such as weather, water flows, and soil nutrients. The last column in Table 5 shows how each package simulates crop yields.
As farmers cannot know at planting time, how much they will actually harvest at the end of the year, most software packages contain modules for explicit simulation of expectations, especially about crop yields. In IMT and CATCHSCAPE the expected water supply and expected yields are the actual simulated values from the previous year, also called naïve expectations. This is also possible in MP-MAS, by setting the coefficient $\lambda$ in Equation 1 to zero. But MP-MAS also allows for more gradual adjustments by setting $\lambda$ to greater than zero. MP-MAS is also the only package in which agents update price expectations.

The other software packages used different approaches to expectation formation. For instance, ECECMOD has no internal updating of expectations but approximates expectations (about crop yields, N absorption, weed development, ammonia losses and several other biophysical conditions) from average simulated values of model pre-runs for each soil type and each agronomic practice. SAM assumes farmers will apply optimum amounts of N fertilizer, but reduces the amount if soil moisture at the beginning of a period falls below a threshold level, as farmers expect drought. In the case of ABSTRACT, agents in the upstream and floodplain areas form their expectations about the water availability in the dry season, by comparing the actual water availability in the preceding wet season to a threshold level (defined in the input data); agents in the downstream area form their expectations from the actual amount of water collected in a reservoir.

5.5 Model integration and software coupling

Approaches to model integration and software coupling fall into two classes. First, embedded coupling is an approach in which all model components are incorporated in the same source code, which often involves rewriting or merging existing code into the code of the integrated model system. This type of model integration has been applied for CATCHSCAPE (written in
SmallTalk), LUDAS (NetLogo), PALM (Delphi), ECECMOD, IMT, and MP-MAS (+EDIC/+TSPC). For large model components or models developed in interdisciplinary research teams, this practice is usually impractical and run-time software coupling might be preferable. This class of external coupling includes SIM, MP-MAS (+WASIM ETH/+LUCIA/+EXPERT N).

A further distinction can be made in the frequency of interaction between the land use decision module and the biophysical module in each software. For instance, ABSTRACT loops through its set of decision heuristics at 10-day time steps, equal to the hydrology module. If the algorithm finds a date to plant, it evaluates the expected water availability and if enough, chooses a crop based on a random probability function that reflects the crop preferences of the respective agent group. Also PALM simulates agent decisions using heuristics at the same time steps as the biophysical module, and considers farm activities in great detail, including planting, fertilizing, weeding and milking.

All other simulators execute the land use decision module and the biophysical module only once per period. For example, MP-MAS simulates the agent land use decisions for a whole year and then simulates the biophysical processes and crop yields. There is hence no updating of land use decisions within one period in response to environmental changes. An exception is MP-MAS (+EDIC/+WASIM ETH) with irrigation, in which agents irrigate their plots at monthly time steps and change their original land use plans in case they receive less irrigation water than expected.
5.6 Limitations of MP-MAS

MP-MAS has several limitations as the software package was developed case-by-case to capture the particular research questions in the six aforementioned applications. It would be possible to address these limitations in future versions of the software.

MP-MAS is limited to simulating the decision-making of farmers; other agents such as landowners and water user associations are represented with highly simplified decision rules. CATCHSCAPE, for instance, models the decision-making of other agents such as government agencies, industries, and non-farm households. MP-MAS is therefore not suitable for modeling situations in which farmers compete for resources with non-farmers.

Moreover, agents in MP-MAS cannot yet coordinate their decisions. 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 or to dam a river. 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 or dam. We note that none of the other simulation packages allows for endogenous collective action to emerge. Work is
ongoing to implement group decision-making of user associations in MP-MAS, for example, for joint investment and marketing activities.

Different from CATCHSCAPE, LUDAS and IMT, 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.

6 Conclusion

The strength of the MP-MAS software package is in its combination of the following three aspects:

1. The use of constrained optimization to simulate decision-making of farm households gives MP-MAS a strong footing in microeconomics and farm management theory. It is unique in separating investment, production, and consumption decisions, and by including price expectations and market dynamics.

2. The use of an agent-based modeling approach allows MP-MAS to capture much economic and environmental heterogeneity among agents; it also allows capturing interactions between agents, and facilitates the combination with spatial modules simulating environmental dynamics. With regard to technology diffusion, MP-MAS is unique among integrated models of agricultural systems in combining the communication of innovation information with the microeconomic evaluation of new technologies.

3. Various optional modules for environmental dynamics allow users to tailor their MP-MAS application to different purposes and different levels of data availability. Modules for water
flows and soil nutrient changes are available at both coarse and fine temporal resolutions. In addition, MP-MAS can be coupled at run-time to process-based external software packages such as WASIM-ETH, LUCIA, and EXPERT-N.

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