Chapter: Illustrating a new 'conceptual design pattern' for agent-based models of land use via five case studies—the MR POTATOHEAD framework

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26 July, 2006

Final version submitted for publication in "Agent-Based Modelling in Natural Resource Management," Adolfo López Paredes and Cesáreo Hernández Iglesias, eds.

Abstract

This chapter presents a "conceptual design pattern" (CDP) that represents key elements of standard ABM/LUCC models in a comprehensive logical framework and includes basic functionality and data often present in ABM/LUCC models. The CDP illustrates the key building blocks for ABM/LUCC models, creating a template to assist scholars new to the field to understand existing models and design their own models. Second, the framework facilitates direct comparison of the structure and function of existing models. We present five separately developed models within this framework (SLUDGE, SOME, FEARLUS, LUCITA, and SYPRIA), demonstrating how multiple models can be represented and compared within the same meta-structure. The exercise highlights elements common to all models, demonstrates the unique contributions of each model, reveals commonalities between models, and highlights processes associated with land-use change that are not covered by our models. The CDP as presented here is very much a work in progress, and we welcome feedback from other ABM/LUCC developers, in the hopes of ultimately developing a shared model representation that will accelerate the development of not only ABM/LUCC, but also the theory of land-use change.

1 Introducing a new conceptual design pattern

1.1 ABM/LUCC: towards a common representation

The natural landscape houses a wide variety of renewable and non-renewable resources, such as forests, water, agricultural soils, grazing land, and species habitat. Land use decisions often affect the stock, quality, and sustainability of many of these natural resources. Because these resources provide ecosystem services that contribute to human well-being, many natural resource managers are interested in modelling land-use decisions and land-use change. In recent years, application of agent-based models of land use/land-cover change (ABM/LUCC) has grown. ABM/LUCC models combine representations of key actors whose decisions affect the landscape (such as farmers, residents, developers, and regulators), a virtual representation of the landscape under study, and a series of environments through which agents interact with the landscape and one another. A series of recent works review ABM/LUCC models in greater detail, focusing on motivation for their use, conceptual challenges in their development, and appropriate roles for their application (Benenson and Torrens 2004; Bousquet et al. 2003; Brown et al. In preparation; Crawford et al. 2005; Parker, Berger, and Manson 2002a; Parker et al. 2003; Verburg 2006)

Many of these works discuss the challenge of communication for an ABM/LUCC. This challenge is not unique to LUCC applications of agent-based modelling, but is common across computational simulation models in many fields. The language of mathematics provides a framework for model expression, communication, and evaluation for formal analytical models. As noted by computational scholars in many application areas (individual-based modelling/ecology (Grimm et al. Forthcoming), economics (Fontana 2006), general social science (Hales, Rouchier, and Edmonds 2003; Richiard et al. 2006), and computational biology (Krieger 2006), as well as land-use modelling (Parker 2005b)), such a shared framework is missing, but needed for computational simulation models. Such a framework could take the form of a single meta-model that embeds common features of two or more conceptually related models, such as the TRAP class described by Cioffi-Revilla and Gotts (2003). It could not only aid communication, but could also facilitate model replication, code sharing, and the development of theoretical foundations.

This chapter presents a "conceptual design pattern" (CDP) that represents key elements of standard ABM/LUCC models in comprehensive logical framework. The

CDP includes basic functionality and data often present in ABM/LUCC models. Its development and presentation has several goals. First the framework illustrates the key building blocks for ABM/LUCC models, creating a template to assist scholars new to the field to understand existing models and design their own models. Second, the framework facilitates direct comparison of the structure and function of existing models, even if those models are developed using different modelling toolkits or programming languages. Through presentation of five separately developed models within this framework, we demonstrate how multiple models can be represented within the same meta-structure. Third, we hope that this framework will be a first step towards development of a set of code libraries, through which a variety of models can be built and compared. A set of such libraries may allow ABM/LUCC modellers to achieve their own version of the future envisioned by pioneers in computational biology: “a future in which not just … models but all the pieces of models should be sharable. In this utopia, models should be able to swap computer code … as easily as Mr. Potato Head swaps noses.” (Krieger 2006, p. 189)

1.2 "Mr. Potatohead" CDP

Figures 1-6 illustrate the elements of the MR POTATOHEAD (Model Representing Potential Objects That Appear in The Ontology of Human-Environmental Actions & Decisions) CDP. Elements are divided into six conceptual superclasses: *Information/Data, Interfaces to other models, Demographic, Land-Use Decision, Land Exchange,* and *Model Operation*. Although model elements are divided into "classes" containing in some cases both "functions" and "data," the framework does not necessarily correspond to the actual design pattern or code structure of any existing model, nor does the term “class” necessarily refer to a single class of objects within a model. The template represents a list of design considerations, rather than a strict set of objects, and models based on this template could be represented in either an object-oriented or non-object-oriented language. As well, many key behind-the-scenes programming structures, such as databases, are not represented.

In the CDP, bullets (•) represent generic elements, and dashes (-) are potential subclasses/examples. Most models will not contain all elements. Minimum elements that we see as required for a basic functioning model are marked with an asterisk (*). Thus, if a modeller were to select an option for each of these required elements, the framework could be used to customize a particular implementation of the standard model. Similar to the historically popular "Mr. Potatohead" toy (PLAYSKOOL), in which the user chooses feature elements from a diverse set of choices to create a recognizable but individualized Mr. Potatohead, we hope that a modeller can use our template to design (or represent) a particular implementation of an ABM/LUCC model. The following sections describe each superclass and their elements.

1.2.1 Information/Data classes

The *Landscape Representation* class describes the spatial structure of, and data contained in, the virtual landscape on which the model operates. ABM/LUCC models can operate over both theoretical and real-world landscapes, using both raster and vector representations of space (Berger and Parker 2002; Brown et al. 2005a; Parker 2005b). Parcel sizes can be fixed, expand through acquisition of multiple cells, or be subdivided through parcelisation (Lei et al. 2005). (A parcel is defined as a land management unit composed of one or more contiguous cells.) Agents may be able to own multiple parcels, and parcels may be subdivided into multiple management units.

Parcels may be occupied by a single or by multiple agents. A landscape representation may include multiple data layers, such as the essential land use layer, and also land ownership/occupancy, land cover, soil types, etc.

Additional *Spatial Data Inputs* (potentially derived from or linked to GIS) may be used in the model at the initialization stage, during the model run, or to produce and analyze output. *Network models* are often essential for calculating transportation costs or tracking hydrologic flow (Berger 2001; Lei et al. 2005). Networks can also represent information channels, species migration paths, etc. *Neighbourhood Effects* play an important role in many ABM/LUCC models (Caruso, Rounsevell, and Cojocaru 2005), with most models implementing fixed-radius effects for technical reasons. *Non-spatial networks* representing family and social connections, trading partners, and group affiliations may also be present (Barreteau et al. 2004).

Institutional/Political and Economic factors play important roles in almost all LUCC models. Any model must specify rules that govern land tenure (ownership, occupancy, use, acquisition, and rights) and land transfer mechanisms. Zoning constraints are often important, especially in urban contexts (Zellner In Review; Zellner et al. 2003). When profitability influences decision making, taxes, subsidies, and land preservation programs affect relative payoffs to various land uses. Since local prices for particular land-use outputs may depend on the local level of their production, some ABM/LUCC models represent local markets for input and outputs. Global, or fixed economic parameters such as world commodity prices will also affect relative payoffs to land uses.

Finally, since all *Potential Land Uses* may not be utilized in any given simulation, we represent these as a separate class, along with specific *Factors Affecting Land Productivity*.

1.2.2 Interfaces to other models

Given that many ABM/LUCC models are designed specifically to study feedbacks between land-use choices and their environmental impacts, modellers often choose to couple the ABM/LUCC with external *Biophysical Process Models (Parker and Berger 2002)*. The importance of cross-scale processes and feedbacks for LUCC systems has also been highlighted by many authors (Parker, Berger, and Manson 2002a; Verburg 2006). Thus, some ABM/LUCC models include linkages to coarser-scale *Socioeconomic Models*, especially in terms of obtaining projections for land demand and/or population growth rates (Manson 2006).

1.2.3 Demographics classes

The *Agent* class forms the core of any ABM/LUCC model. Agent types in this class can include any decision maker whose decisions affect land use and/or cover. Most models will include agents with direct decision making power over a parcel for which they hold use rights and/or ownership, such as farmers and suburban residents. LUCC agents can also control decisions less directly, or control a subset of rights for the land (such as landlords, developers, and zoning boards). Any agent must possess an *Agent Decision Model* that has two functions: *Calculate Payoffs*, which determines the pecuniary and non-pecuniary payoffs for that agent of particular land-use choices, and *Decision Strategy*, which determines how payoffs are translated into a land-use decision. A wide variety of decision making strategies are incorporated in various ABM/LUCC models, and few structured comparisons have been undertaken of the implications of various decision strategies, although there is broad interest in this question (Parker et al. 2003). Agents may differ according to their *Internal Characteristics*, including cultural identity, human capital, length of time into the future for which they plan (time horizon), weight that they place on future payoffs relative to current payoffs (discounting), and attitudes towards risk. Agents may also possess different levels of *External Resources*, such as physical, financial, and social capital. These internal and external attributes may affect their decision-making strategies, the land-use choices available to them, and the level of payoffs that they obtain from particular land uses.

Demographic Dynamics describe the global rules by which agents enter and leave the model (*In-migration* and *out-migration*, *Reproduction*, *Birth/Death*, and *Household Division/Agglomeration*), and make transitions through their life cycles (*Aging*, *Marriage*, and *Succession*). The processes described in this class may alter agent attributes (such as age and marital status), and as well agent characteristics may affect whether demographic events occur.

1.2.4 Land-use decision class

The *Land-use Decision* class is also central to any ABM/LUCC model. This class relies on the *Agent Decision Model* described above. Decisions are likely to be influenced by the internal characteristics of the agent, such as previous experience. The class also relies on data inputs relevant for the particular parcel(s) for which the agent makes decisions. Potential land uses determine the choice set over which the agent calculates payoffs and makes decisions. Many external data elements will affect these payoffs, including land tenure rules, local economic conditions, parcel accessibility, biophysical suitability, and neighbourhood effects. Notice that this class simply calls data and functions from other classes. It thus reveals the specific determinates of land use for a particular model.

1.2.5 Land Exchange class

Many, but not all, ABM/LUCC models allow exchanges of parcels between agents. Inclusion of such exchange mechanisms can be very important when questions such as patterns of ownership and distributions of holding size are central to the research questions the model is designed to address. *Land Exchange* mechanisms require three elements. *Suppliers of Land* may offer land due to profit motives, out-migration, or as part of the household life cycle. They will have rules that determine the parcels they will supply and the term under which they will transfer the parcels. *Acquirers of Land* may have similar complementary motives, parcel acquisition targets, and terms they will offer for parcels. *Exchange Rules* govern the timing of land transfers, including when particular agents will consider or be able to participate in exchanges. *Allocation Mechanisms* define the types of land transfer-market or non-market-and the rules through which it takes place. (Note that two agent decision functions (land supply and land acquisition) are described in this class.)

1.2.6 Model operation class

The *Model Initialization* class defines the model's initial conditions for all data types, including the landscape, the agents that occupy it, and values from external models. Land-use systems are often highly path dependent, and thus outcomes in agent-based models often vary according to the initial conditions of the model (Brown et al. 2005b; Parker 1999; Verburg 2006), or according to random seeds. For this reason some practitioners generate distributions of model outcomes, or report results based on non-parametric statistical tests of model outcomes (Gotts, Polhill, and Law 2003; Polhill, Gotts, and Law 2001). Path dependence can also result through the temporal sequence of action in a model (event sequencing). *The Temporal Dynamics* class specifies the number of iterations the model runs for and how event sequencing is handled. Models may adhere to a discrete time system specification, where events in each iteration of the simulation follow a specific fixed schedule. Alternatively, the model may adhere to a discrete event system specification, where future events in a simulation run are dynamically scheduled on the basis of current events, and there are no uniform iterations per se (Zeigler, Praehofer, and Kim 2000). Temporal dynamics may be designed to minimize path dependence, to mimic real-world dynamics, or with other goals in mind.

2 Representing existing models in the CDP

In this section, five separately developed models are represented in the MR POTATOHEAD CDP. The features of each model are noted in Figures 1-6. Model-specific version of the CDP for each model, with greater detail, are given in Appendices 1-5, available at http://www.insisoc.org. The written descriptions of each model follow the CDP implementations in the appendices. A table with detailed comparisons of the FEARLUS, LUCITA, and SYPRIA models is published in Parker, Berger, and Manson (2002b), and links to each project page are available at http://www.csiss.org/resources/maslucc/research.php.

2.1 The SLUDGE Model

SLUDGE (Simulated Land Use Dependent on eDGe Effect externalities) is a simple combined cellular automaton and agent-based model designed to explore the effects of positive and negative distance-dependent spatial externalities on economic and landscape pattern outcomes. The model has been used to demonstrate: (a) that free-market equilibrium land market patterns may be inefficient, and Pareto-improving rearrangements of land use are possible (Parker 1999); (b) that spatial externalities are sufficient to generate fragmented development patterns at the urban-rural fringe, which are consistent with definitions of urban sprawl (Parker and Meretsky 2004); and (c) that increases in the magnitude of externalities lead globally to both decreases in economic welfare and increases in landscape fragmentation (Parker 2005a).

2.1.1 Information/Data classes

SLUDGE operates over a cell-based theoretical landscape, with each cell representing one fixed parcel, owned and occupied uniquely by one agent. Abstract landscape layers include land use (urban or agricultural), land rents, and land productivity. Transportation distances to single markets for each land-use type are calculated by Euclidean distance. *Neighbourhood Effects* in the form of positive and negative spatial externalities, which reduce or increase output (respectively) for the affected land use, can be generated by cells sharing borders with the affected cell. With two land uses, four types of externalities are possible.

Land Tenure Rules are simple: agents control land use on the cell/parcel they own, and no parcel exchange is possible. There is a local market for urban land, with the price paid for an urban cell declining as more cells are converted to urban use. The magnitude of demand is controlled through a user-set parameter. Output prices for ag land, productivity for both land uses, and transportation costs to each market location are also set by the user, and are constant for all cells. The user also sets parameters affecting the direction and magnitude of the externalities.

2.1.2 Demographics classes and Land-use decision class

Because the model is designed for theoretical exploration of the relationships between input parameters and outcomes spaces, SLUDGE agents are very simple. Agents *Calculate Payoffs* by estimating profits for each land use for their parcel. Returns to agricultural land depend on total revenue (agricultural price times ag productivity (including externality effects) less total costs (the product of transport cost and distance to market)). A similar calculation determines urban profits, with one important exception. Since price for urban land depends on the demand model (I.4), next period's urban prices will depend on how many cells are in urban use at that time, and on what types of neighbours they have. Each agent estimates an expected price for urban land by estimating a supply curve–the price at which other agents would convert to urban, and the amount they would supply to the market given the externalities they face–and estimates an equilibrium price based on this supply curve and the demand curve. Agents' *Decision Strategy* is to select the most profitable of the two land uses. All agents are identical, are not forward looking, and do not account for or react to risk. The *Land-Use Decision Class* simply implements the agent decision model for each agent, as described below.

2.1.3 Model operation class

SLUDGE has been implemented in two languages, Mathematica and RePast. In the Mathematica version, for *Model Initialization*, users can specify initial input landscapes by defining a raster array, and parametrically setting an urban market location. The current SLUDGE/Repast version either initializes with an all-agricultural landscape, or with a random landscape where each cell has a 50%

probability of each land use. SLUDGE/Repast users can parametrically assign market locations for both land uses. *Neighbourhood Effects* are calculated for initial landscapes, and affect agent decisions from the first round of the model. Agents are each assigned a single cell, and remaining economic parameters are set by the user.

SLUDGE *Temporal Dynamics* are also very simple, and are designed to avoid oscillation and minimize path dependence. The number of iterations is set by the user, but landscapes generally reach equilibrium in fewer than 20 runs. Agents occupying every other cell are active in each time period, and oscillate in a checkerboard fashion. In this equilibrium, land-use locations, quantities, and pattern are jointly determined.

2.2 SLUCE/SOME

As part of the project called Spatial Land Use Change and Ecological Effects (SLUCE), a group at the University of Michigan created an initial model to represent urban growth processes, called SLUCE's Original Model for Experimentation (SOME). The purpose of the model was to support an exploration of the relationships between residential preferences, as observed through social surveys (Fernandez et al. 2005; Marans 2003) and urban settlement patterns, as observed through remote sensing and parcel-based mapping. The model has been used to explore (1) the effects of agent heterogeneity on urban settlement patterns (Brown and Robinson In Press), (2) the degree to which model patterns approximate the power-law distribution of settled patch sizes observed in real cities (Rand et al. 2003), (3) the implications of path dependence for the evaluation of output from urban models (Brown et al. 2005b), (4) the role of zoning urban pattern formation (Zellner et al. 2003), and (5) the effectiveness of greenbelts in containing urban spread (Brown et al. 2004).

2.2.1 Information/Data classes

SOME operates on a cell-based landscape. Several versions of the model allow only one resident or service centre per cell, but a modified version allows multiple residents or service centres within each cell (Zellner et al. 2003), with variable levels of density allowed and expressed by a theoretical or actual map read into the model. The latter approach facilitates introduction of zoning, based on lot-sizes, into the model. The basic landscape the model interacts with has three primary attributes: aesthetic quality, whether or not the cell is occupied by a resident or a service centre, and distance to service centres. At initialization, the aesthetic quality values can be created as a theoretical landscape, or read from a GIS-based data file (e.g., based on rolling terrain, proximity to water features, land cover, etc.). Similarly, locations of initial residents and service centres can be placed using a set of theoretical assumptions or read from GIS data files. An option in the model allows the user to select whether or not the aesthetic quality values are modified during a run. If updating is selected, aesthetic quality is modified downward as a function of the number of residents and service centres located in the cells immediately surrounding each cell. Based on the locations of service centres, distance to service centres is calculated for all other cells. The distance can be calculated as straight-line distance, or based on a road network that is read from a GIS file (Brown et al. 2005b).

2.2.2 Demographic classes

Residents calculate the current utility they obtain from a sampling of locations and select the location that provides the greatest utility. The sampling process is included to reflect the incomplete information available to residents. The agents do not attempt to anticipate future returns in the model. The utility calculation can consider levels of aesthetic quality, distance to services, density, and/or similarity to neighbouring residents. Each of these factors is weighted according to the preferences of the residents, which can be established theoretically (Brown et al. 2004) or on the basis of survey responses (Brown and Robinson In Press; Fernandez et al. 2005).

Residential agents are created during a model run at a user-specified rate. This rate can be constant, or can change over time and can be calibrated so that it approximates an observed rate of residential development (Brown et al. 2005b). Service centres, likewise, are created at a rate specified by the user. This is expressed as the number of residents per service centre in the entire region. When a resident or service centre moves into a location (i.e., a cell) that location remains occupied by the same resident or service centre for the entire model run.

2.2.3 Land Exchange class

Because residential agents always create residential land use, and service centre agents always create service centres, the agents do not make a land-use decision per se. Rather, they make a decision about where to engage in their designated land use. So the fundamental decision is one of land exchange. There is no explicit land seller in the model. Rather, the model reflects a situation in which the value of land for residential or service development is assumed to exceed the value of land for other uses. The model is therefore demand driven. The demand is determined by the number of residents, and by their location preferences.

2.2.4 Model operation class

Versions of the SOME model have been implemented in three different environments. The first version was written in Objective-C with Swarm; a simpler version was implemented in NetLogo; and a revised version was implemented in Repast. This version has evolved sufficiently that it has essentially become a new model. Model dynamics are synchronous, such that all agents in a given time step carry out their actions in random order before variable values are updated for the next time step. Once an agent has performed its actions during the time step in which it chooses a location, it is no longer active. Interaction between agents is, therefore, only indirectly achieved through changes to the environment.

2.3 FEARLUS

FEARLUS (Framework for the Evaluation and Assessment of Regional Land Use Scenarios) is a family of models aimed at modelling land use change using agent-based social simulation, focused on investigating the relative success of alternative agent decision models in various environments. Work with FEARLUS has added functionality as the behaviour of simpler models is understood. Early work (Polhill, Gotts, and Law 2001) used version 0-3, later work (Gotts, Polhill, and Law 2003) version 0-5, and more recent work coupled a land market model (Polhill, Parker, and Gotts 2005) with version 0-6-7. Functionality provided by version 0-6-7 is discussed here. However, particular investigations often entail simplification of model configurations for more formal analysis (Gotts, Polhill, and Adam 2003), demonstrating the complementarities between simulation and mathematical work also found by other researchers (Brown et al. 2004; Galan and Izquierdo 2004)

The representation scheme in FEARLUS is somewhat abstract: the biophysical model is based on bitstrings, inspired by the work of Epstein & Axtell (1996). For the purposes of comparing decision algorithms, all that matters is that at each location in space/time, there are a range of decisions to take with different outcomes for each land manager: in this case, the economic return obtained from a particular choice of land use.

2.3.1 Information/Data classes

FEARLUS operates over an abstract, cellular landscape. Agents may own multiple parcels, with each cell-based parcel having a unique land use. Biophysical characteristics are represented using a bitstring (one for each land parcel) that does not change over time once the model starts. During initialization, these bitstrings can be "clumped" (adjusted to make neighbouring land parcels more similar to each other). Two *Neighbourhood* definitions are possible. Physical hexagonal, Moore and von Neumann neighbourhoods can be defined with a specified radius. Social neighbourhoods are defined as the set of land parcels owned by land managers who own the land parcels physically neighbouring those owned by a land manager. Since ownership of land changes over time, the social neighbourhood also changes, with the result that FEARLUS models are not typically strict cellular automata (Gotts, Polhill, and Adam 2003). Neighbourhoods mainly affect social interaction for the purposes of imitation. As a result, the set of land parcels that physically neighbour a land parcel (as determined by the topology), matters less than the social neighbourhood, although the two are linked, and physical neighbourhoods are used when land managers exchange land parcels.

The climate and economy are represented using bitstrings. There is no spatial variation in either, but both can have parameterised rates of change or have particular sequences of bitstrings specified in a file. Since their effect is similar in FEARLUS, the climate and economy are referred to as the external conditions. Land uses are also represented using a bitstring, and the economic return of each land parcel is based on how well the bitstring of the chosen land use matches with the local biophysical characteristics and the temporally-varying external conditions, less a break-even threshold parameter. The break-even threshold parameter, which is spatio-temporally constant, causes some land use decisions to return a loss to the land manager.

2.3.2 Demographics classes

Since the persistence of an agent in FEARLUS depends only on whether they have to sell off all their land, the agents are best conceived of as households. Agents are mainly responsible for choosing the land use to apply to their land, and parameters controlling this algorithm are set according to the subpopulation they belong to. Agents thus store the algorithm they use to choose land uses, the subpopulation to which they belong, and information pertinent to the decision, such as earlier climatic and economic decisions, and the land uses and yields applied to the parcels they own. For imitative strategies, the amount of weight to give to neighbouring experiences of land use as opposed to the agent's own experiences is also stored. Agents store their wealth, which is used to determine the need to sell land and eligibility to buy it. The age of the agent is also stored for observation purposes.

2.3.3 Land-use decision class

The *Land Use Decision* algorithm in FEARLUS is set by the subpopulation to which each agent belongs. The parameters for each subpopulation specify distributions of key aspects of the land use selection algorithm, potentially allowing each member of a subpopulation to have a slightly different land use selection algorithm. However, the basic structure of the *Land Use Decision* algorithm for all agents is the same, and is applied to each land parcel owned independently:

1. The yield of the land parcel is compared with the land manager's aspiration threshold (for which the subpopulation defines a distribution). If the aspiration threshold is met or exceeded, then the land manager is said to be content with the land use decision, and typically uses the same land use in the following year.

2. If the aspiration threshold is not met, then there is a random probability (specified by a distribution at the subpopulation level) that the agent will try an imitative or an experimental strategy to find a new land use. Imitative strategies involve mechanisms for selecting a land use from the set of land uses that appear in the social neighbourhood, such as selecting based on the number of times the land use occurs, or how much yield each land use has generated. Experimental strategies select from the set of all land uses, the simplest of which is to choose one at random, though other strategies are available.

2.3.4 Land Exchange Class

The Endogenised Land Market Model (ELMM) (Parker, Polhill, and Gotts 2006; Polhill, Parker, and Gotts 2005) describes how the accumulated wealth of land managers affects their land holdings. Land managers with negative accumulated wealth are regarded as being bankrupt, and must sell all their land. Land managers with sufficient accumulated wealth (determined by an individual threshold) use a bidding strategy to decide how much they would offer for neighbouring land parcels that are available for sale. Bidding strategies vary from simple heuristics such as offering a certain proportion of wealth, to more sophisticated techniques involving computing a bid price based on the discounted estimated profit from the land. Having determined the price they would offer for land parcels, the land managers then use a selection strategy to decide which parcels they will put in a bid for. An example selection strategy is to choose the *n* highest offer price land parcels while the total offer price is within the budget of the land manager. This would be with a view to accumulating fewer good quality (in the eyes of the land manager) parcels, as opposed to an alternative strategy, which is to select the *n* lowest offer price land parcels, with a view to acquiring as many parcels as possible. Having gathered the bids of existing land managers for the land parcels for sale, a bid is generated from a potential incoming land manager, and an auction used to determine the new owner. There are two options for the auction: one a straightforward first price sealed bid auction, where the highest bidder wins and pays the price they bid. The issue with such auctions is that it is not necessarily rational to bid the valuation price, since a price a minimal amount above the second-highest bidder is sufficient to win. The second option is therefore to provide for a Vickrey auction, in which the highest bidder wins, but the price paid is that of the second-highest bid.

2.3.5 Model operation class

FEARLUS uses a separate schedule to initialize the model. This sets the biophysical properties and initial land uses and external conditions, and creates the land managers, assigning each an equal number of land parcels. FEARLUS can be configured to use separate random seeds for the initialization than for the rest of the model, enabling runs to have the same initial set-up but potentially different outcomes.

The main schedule in FEARLUS consists of a cycle in which all of the agents decide their land uses; the external conditions are determined; the economic return to each land manager is calculated; and exchange of land is carried out where appropriate. This discrete event schedule has a fixed structure, and no agent can access the decision of another agent until all agents have made their decision. Simulations are typically run for a number (usually 200) of cycles (each of which is intended to represent a year).

2.4 LUCITA

LUCITA (Land-Use Change In The Amazon) refers to a series of simulations (Deadman et al. 2004; Lim et al. 2002) designed to explore the factors driving land use change in the Brazilian Amazon near Altamira.

2.4.1 Information/Data classes

LUCITA utilizes a set of raster grids, with a cell size of 1 ha, to represent the landscape along the Trans-Amazon Highway west of Altamira. Separate georeferenced grids are created to represent land cover, property parcels, and soils. Property parcels in this area have an average size of about 100 ha, but vary in size and shape. The study site includes just over 3900 properties, arranged along the Trans-Amazon Highway and a series of side roads that run perpendicular to the main highway at about 5 km. intervals. Each property contains roughly 100 cells and remains fixed during a simulation. Household agents each hold one property during a simulation run, but may pursue different agricultural practices on each cell in the property. As agents are added to the simulation, they select an available property on the basis of its location relative to the main highway and the distance from Altamira. Household agents have secure tenure to their property unless they become bankrupt, at which point they abandon the property. Abandoned properties are available for occupation by a new household agent. A household with sufficient financial capital to meet its labour requirements is able to seek out labourers from a labour pool, composed of adult male farmers who have been removed from their plot because of the incurrence of excessive debt. If hired, a labourer's wealth is increased and the level of available labour in the pool is decreased.

2.4.2 Interfaces to other models

A set of biophysical process models govern vegetation growth in LUCITA. Abandoned cells enter a state of *secondary succession* for 8 years, and then transition to forest. A more sophisticated process model determines *soil fertility* and *crop yields*. Each cell in the soil grid holds an object that adjusts nutrient values in response to the land-use activity occurring on the corresponding cell in the land-cover grid. For example, when a cell in the land-cover grid is cleared and burned, nutrient values in the corresponding soil-grid cell are altered to represent nutrient deposition. When a crop is planted and harvested on a particular land-cover grid cell, nutrient uptake by the crop depletes the soil-nutrient values in the corresponding soil-grid cell. Initial values for some soil parameters, soil changes through land-cover clearing and burning practices, and crop-yields are calculated based on regression equations developed by Fearnside (1984; 1986; 1988). Some of the parameters, such as those relating to climate or specific soil-distribution levels, are based on documented statistics and fixed or randomly set within observed ranges.

2.4.2 Demographics classes

The agents in LUCITA represent farming households that arrive on the frontier over time. Each agent contains a number of demographic parameters and variables including: household composition by age and gender, fertility and mortality rates, participation rates for farm related activities, and household capital resources on arrival. Five cohorts of households are identified, based on their time of arrival on the frontier, each with their own demographic characteristics. Household demographic parameters and variables are randomly assigned using a normal distribution based on the mean and standard deviation for the cohort within which they belong.

2.4.3 Land-use decision class

Household agents utilize heuristics to make land use decisions on a cell-by-cell basis. In each round of the simulation, households initially allocate labour and capital resources to meet subsistence requirements and maintain existing crops. Remaining surplus labour and capital resources are then allocated to converting cells to grow either annuals, perennials, or pasture. Agents have full knowledge of current commodity prices and the cost of inputs. When a household agent arrives on an unoccupied property, the land is entirely forested. Agents will start by clearing and converting cells nearest to the road, moving backwards into the property over time. The decision regarding which specific crop to grow is based on a number of factors including: subsistence needs, soil quality, the specific labour and capital inputs required for that crop, the current land use, the availability of outside labour, and the quality of the burn when forest has been cleared. Agents typically maintain annual or perennial crops on a cell for as long as yields meet or exceed expected levels.

2.4.4 Model operation class

LUCITA is implemented in RePast. Initially, the landscape is entirely forested with the road network and property parcels established. A simulation run typically lasts 30 years, representing the period from 1970 to 2000, where one iteration of the simulation represents one year. Each iteration of the simulation follows a predefined schedule of events in which new agents are added to the simulation, land use decisions are made and implemented, crop yields are calculated, land use and soil quality grids are updated, agent variables are updated, unsuccessful agents are removed, and output information is generated. Simulations can be implemented with a homogeneous collection of agents, or with heterogeneous agents whose characteristics vary according the demographic cohort within which they arrived.

2.5 SYPRIA

The Southern Yucatan of Mexico is home to forests that the United Nations has declared a global 'hotspot' of biological diversity. They are also threatened by 'slash-and-burn' agriculture that supports a rapidly growing rural population. The Southern Yucatan Peninsular Region Integrated Assessment (SYPRIA) is an agent-based model of land change in this region. SYPRIA represents actors and institutions with two separate agent-based models and the environment with a cellular automata model. This actor-institution-environment formulation allows SYPRIA to model land change by representing the interplay over time among actors, between actors and institutions, the effects of actor decisions on the environment, and the effects of environmental dynamics on actor decision making (Manson 2000, 2005, 2006, 2004).

2.5.1 Information/Data classes

Agents reside in a model landscape comprised of a two-dimensional grid. Every location in the real study site has a corresponding grid cell in the model landscape that stores variables representing features of interest in reality, such as land use, soil type, or political jurisdiction. Agents can have multiple land holdings that correspond to agglomerations of cells mapping onto parcels in the real world, although each cell is limited to a single land use. All three submodels are calibrated and validated with data derived from remotely sensed imagery, in-depth interviews, field research, and spatial socioeconomic and environmental data sets. In addition to social and ecological information based in the landscape, agents have individual characteristics based on household interviews. Other institutional and spatial data and classes are noted below.

2.5.2 Interfaces to other models

The environment submodel controls landscape variables not affected by agents. The environment submodel uses the same grid of cells used to represent the landscape in which agents reside. It modifies variables related to environmental phenomena, such as land cover or soil type, according to a series of rules that incorporate variables from adjacent cells, previous cell states, and external factors. A population agent, in essence an external model, controls the rate of population growth and migration dynamics. Agents are responsible for internal household dynamics such as age structure.

2.5.3 Demographics classes

As noted above, SYPRIA divides agents into actors and institutions. Both possess characteristics that influence their behaviour (e.g., each SYPR household in reality has varying labour or capital endowments that are represented in its corresponding actor-agent). Agents interact with one another (e.g., an institution-agent for local government can give subsidies to one actor-agent while limiting those for another). Actor-agents incorporate landscape variables into their decision making (e.g., an agent representing a household seeks to cultivate crops on land with good soils). Actor-agents can also change some of these cell variables, such those corresponding to current land use, while institution-agents can modify others, such as those relating to permissible land uses.

2.5.4 Land-use decision class

A key innovation of SYPRIA is use of genetic programming to model actor decision making (Manson 2004). Genetic programming uses the computational equivalent of natural selection to evolve software programs to find solutions in highly dimensional and noisy environments. These programs serve as multicriteria evaluation strategies for household agents. Each possesses a population of genetic programs that are calibrated against household surveys, parcel data, land use/cover data, and data associated with the environmental and institutional model components. Genetic programming is emerging as a valuable means to model decision making and test hypotheses stemming from competing theories of decision making (Edmonds 1998). During each simulated year, every actor-agent chooses from its collection of strategies the one that best suits its current needs. Actor-agents improve their strategies over time (i.e., learn) by testing them against changing social and environmental circumstances (Manson 2005).

2.5.5 Land Exchange Class

Land exchange in SYPRIA is a market-community property hybrid that reflects the changing state of property ownership law in Mexico. As noted above, households use genetic programming to make land use decisions for individual cells and parcels of land. Households take into account internal characteristics (e.g., age, ethnicity, and labour availability) and external considerations (e.g., institutional limits to land use and environmental considerations of the land in question). Households plan for either subsistence or market agriculture on cells that they either possess or that are free for the taking. Available land is available on a first-come first-served basis to eligible households, where institutions impose limits on households based on their membership in different institutions. Households do not pay for land they use, but they can only claim land they can keep under active cultivation. This situation is changing rapidly, however, as Mexico adopts private property rules in rural areas. SYPRIA agents with sufficient resources can now 'buy' land with the permission of a local community council, who acts as the seller of currently unclaimed land.

2.5.6 Model operation class

SYPRIA is written in C++, integrating with IDRISI GIS. SYPRIA recreates the landscape of SYPR as it was in 1970 and then simulates land change on a yearly basis to a variety of end dates. Three processes take place each simulated year. First, institutions change variables related to actor decision making (e.g., institution-agents change the extent of conservation programs in landscape cells or granting subsidies to individual actor-agents). Second, the environment responds to actor behaviour and ecological dynamics. Third, actors make decisions influenced by institutional and environmental factors.

3 Discussion and Conclusions

While all of the authors previously participated in an informal comparison of their models, in which each author answered a specific set of questions for their research site and model implementation (Parker, Berger, and Manson 2002b), this is the first attempt by the authors to compare their models in a common framework. What do we see as the value added through this exercise?

The lead author has gained a much better understanding of the operational details of her co-authors' models. In spite of having previously read detailed descriptions, seen multiple presentations by her co-authors, and covered their articles in her classes, this process revealed many new details. This experience reflects the commonly recognized issue of communicating model structure and mechanisms discussed in the introduction, as relevant details are often not suitable for inclusion in journal articles, and yet can have a profound influence on the models' behaviour. While communication can be addressed in part through appropriate licensing of software to permit access to models' source code, there is a clear onus on authors of such models both to provide further resources to facilitate understanding of their creations, and to participate in collaborative exercises aimed at developing a common approach. Though the scope for commonality may be constrained by socio-cultural and biophysical particularities of the different scenarios to which the models are applied, this exercise has shown that there are sufficient commonalities to begin to identify what an agent-based land use change model generally looks like.

Key elements common to the majority of models are clearly revealed. While we would need a more representative sample of models to draw more general conclusions, this effort begins to reveal a minimum element set for a shared code library—in essence, a proposed basic eyes, nose, mouth, and ears for Mr. Potatohead. We find that all the models fit into the proposed framework, and the comparison validates the framework, to some degree, as a useful starting place for building a general library.

The unique contributions of each model are also revealed. For example, SLUDGE, and FEARLUS both model land demand (in residential and agricultural settings, respectively). FEARLUS is unique in having a land allocation mechanism based on bidding. Among the models covered here, LUCITA uniquely allows exchange of labour between households. SOME models the role of local service and employment centres, drawing on recent recognition of polycentric development in urban areas. SYPRIA models institutional influences and includes endogenous interactions between institutional and land manager agents.

Areas of emphasis common to two or more models are also revealed. For example, SLUDGE and SOME share representation of neighbourhood amenities consistent with their emphasis on residential development at the urban-rural fringe. Consistent with their focus on frontier regions, LUCITA and SYPRIA emphasize household composition and resources, and explicitly model the impacts of cropping choices on soil fertility. FEARLUS and SYPRIA each implement a variety of potential decision-making models, allowing direct comparison of different strategies within the same model. FEARLUS, LUCITA, and SYPRIA all include out-migration of financially unsuccessful land manager agents.

Identification of these areas of common emphasis suggests opportunities to compare models at the algorithmic as well as the structural level. An exercise replicating the behaviour of SugarScape in MASON (Bigbee, Cioffi-Revilla, and Luke 2005) demonstrated how sensitive some model effects can be to the order in which events are scheduled.

The comparison reveals processes that we have identified as important for LUCC that are not covered by our models. For example, none of our models explicitly model the decision to sell land, or allow partial sales of land holdings, and agents in our models do not evaluate or respond to risk. The number of households is also fixed. The lack of coverage of these concepts in our models is not necessarily a problem, as long as these processes do not play a critical role in land-use change in our study areas. Agent-based models can easily become so complex that it may be difficult to understand linkages between model mechanisms and model outcomes, and so it makes sense to focus our models on a specific subset of features of the real-world system. This subset can be influenced by the particular research questions under investigation, which themselves may be influenced by the disciplinary perspectives from which the models are developed. That said, it is worth considering under what circumstances these specific models should be modified to cover some of the identified gaps, and when new models need to be built to focus on questions related to these gaps.

Thus the CDP has been useful by clarifying what processes our models represent, and what they leave out. This could be useful to those seeking to better understand the current state of the field, and to choose which models to study in detail when developing their own. In an ideal world we would also like to create a centralised repository of “MR POTATOHEAD metadata,” where research teams could create a description of their models using web-based forms.

The MR POTATOHEAD CDP is very much a work in progress. Since the case studies presented here represent only a small segment of ongoing ABM/LUCC modelling efforts, we welcome feedback and comments from other modellers. This feedback will be incorporated in future refinements of the CDP, in the hopes of developing a framework that will accelerate both methodological progress for ABM/LUCC and the development of a science of land-use change.

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Pseudo-class templates for “Mr. Potatohead” generic ABM/LUCC modelling framework
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9 June 2006

(Bullets are generic elements, dashes are potential subclasses/examples; all elements are probably not represented in most models. Required elements are marked with an *.)

I. Information/Data classes (Figure 1)

1. Landscape Representation

   Structure (Functionality)

   - *Realism
     - Theoretical (SLUDGE, SOME,FEARLUS)
     - Real-world (SOME,LUCIM,SYPRIA)
   - *Spatial data structure:
     - cell-based (raster, hex, etc.) (SLUDGE,SOME,FEARLUS,LUCITA,SYPRIA)
     - vector (SYPRIA)
   - *Parcel structure
     - Fixed (SLUDGE,SOME,,FEARLUS,LUCITA)
     - Variable (SYPRIA)
   - *Agent/parcel relationships
     - One parcel per agent (SLUDGE,SOME,LUCITA)
     - Multiple parcels per agents (FEARLUS,SYPRIA)
     - Multiple agents per parcel (SOME)
   - *Decision-making units
     - Single decision/land use per parcel (SLUDGE,SOME,FEARLUS,SYPRIA)
     - Multiple uses/management units per parcel (LUCITA)

   Data Layers/Themes

   - *Land use (SLUDGE,SOME,FEARLUS,SYPRIA)
   - Land ownership (FEARLUS)
   - Parcel definitions (LUCITA)
   - Land cover (LUCITA,SYPRIA)
   - Land rent (SLUDGE)
   - Productivity/output (SLUDGE)
   - Aesthetic quality (SOME)
   - Biophysical characteristics (FEARLUS)
   - Land manager subpopulations (FEARLUS)
   - Climate (FEARLUS,SYPRIA)
   - Soil type/quality (LUCITA,SYPRIA)
   - Topography (SYPRIA)
   - Roads (SYPRIA)
   - Market locations (SYPRIA)
   - Census data (SYPRIA)

2. Other spatial data inputs (potentially, GIS functionality)
   - Network models
     - Transportation
       - Euclidean Distance (SLUDGE,SOME)
       - Road network (SOME,SYPRIA)
     - Information diffusion (SYPRIA)
     - Hydrology (SYPRIA)
   - Neighbourhood effects
     - Fixed-radius
       - Nearest-neighbour spatial externalities (SLUDGE)
       - Fixed radius neighbourhood density (SOME)
       - Fixed radius (land market and social) (FEARLUS)
       - Environmental process models (SYPRIA, II.1)
     - Variable radius
       - Distance to service centres (SOME)
     - Diffusion/distance decay

3. Non-spatial networks
   - Social
     - Information/Imitation (FEARLUS,SYPRIA)
   - Trade
   - Affiliation (SYPRIA)

4. Institutional/Political rules and constraints
   - *Land tenure rules
     - Occupancy rights (SOME,LUCITA)
     - Use rights (SLUDGE,FEARLUS,LUCITA, SYPRIA)
     - Acquisition rights (SOME,FEARLUS)
     - Transfer rights
   - Zoning
     - Density restrictions (SOME)
   - Regulations related to taxation, subsidies, etc. (SYPRIA)

5. Economic structures
- Local markets for land inputs and outputs (functions)
  - Urban land demand (SLUDGE)
  - Labour pool (LUCITA)
- Economic data values (data)
  - Input prices (LUCITA,SYPRIA)
  - Output prices
    - Agricultural output (SLUDGE,FEARLUS,LUCITA,SYPRIA)
  - Transportation costs (SLUDGE,SYPRIA)
  - Externality benefits/costs (SLUDGE)
  - Break-even threshold (FEARLUS)
  - Subsistence costs (LUCITA,SYPRIA)
  - Taxes
  - Subsidies (SYPRIA)

6. Potential Land Uses
- Urban residential (SLUDGE,SOME)
- Agriculture
  - Generic (SLUDGE)
  - Multiple abstract (FEARLUS)
  - Multiple annual, perennial, pasture, forest (LUCITA)
  - Subsistence vs. market (multiple) (SYPRIA)
- Service centres (SOME)
- Open space (SOME)

7. Factors affecting land productivity
- Parametric settings for each land use (SLUDGE)
- Match between land use, climate, and economic bitstrings (FEARLUS)
- Assessed by agents as function of input layers (SYPRIA)

II. Interfaces to other models (Figure 2)

1. Biophysical process models
   - Hydrology
   - Species colonization (SYPRIA)
   - Secondary succession (LUCITA,SYPRIA)
   - Soil fertility/crop yields (LUCITA,SYPRIA)
   - Disease outbreaks
   - Carbon sequestration
   - Climate

2. Socioeconomic models
   - Population (SYPRIA)
   - Land demand
   - Global/regional markets

III. Demographic classes (Figure 3)

1. *Agent class
    - Generic land owner (SLUDGE)
    - Residential (SOME)
    - Service centre (job and service provider) (SOME)
    - Land manager/farm household (FEARLUS,LUCITA,SYPRIA)
    - Institutional (SYPRIA)
    - Land Lord
    - Estate Owner (Laird)

   *Agent decision model (function)
   - *Calculate payoffs
      - Profit (SLUDGE,FEARLUS)
      - Utility based on aesthetics and distance to service centres (SOME)
      - Expected yield (LUCITA, SYPRIA)
   - *Decision strategy
      - Boundedly rational profit maximization (SLUDGE,FEARLUS, SYPRIA)
      - Utility maximizing, but with incomplete information (SOME)
      - Adaptive (FEARLUS, SYPRIA)
      - Imitative (FEARLUS, SYPRIA)
      - Heuristic (FEARLUS,LUCITA)
      - Satisficing (SYPRIA)

   Internal characteristics (Data)
   - Age (FEARLUS)
   - Parameters governing imitative and decision strategies (FEARLUS)
   - Aspiration threshold (FEARLUS)
   - Minimum wealth threshold for land bids (FEARLUS)
   - Cultural identity/affiliation (FEARLUS,SYPRIA)
   - Cultural preferences/norms
      - Residential preferences (SOME)
      - Cultivation preferences (SYPRIA)
   - Human capital
      - Education (SYPRIA)
      - Expertise
         - Knowledge of soil/crop relationships (LUCITA)
         - Memory of climatic, economic, yield, and land use histories (FEARLUS)
      - Experience (SYPRIA)
   - Household composition (if household)
      - Gender and age (LUCITA,SYPRIA)
   - Time horizon and discount rate
      - Variable (FEARLUS)
   - Attitudes towards risk

   External resources (Data)
   - Available farm labour (LUCITA, SYPRIA)
   - Physical capital (LUCITA,SYPRIA)
   - Financial capital (LUCITA,FEARLUS,SYPRIA)
   - Social capital
      - Reputation
      - Connections in social network

2. Demographic dynamics (global functions and data)
  - In-migration (SOME,FEARLUS,LUCITA,SYPRIA)
  - Out-migration (FEARLUS,LUCITA,SYPRIA)
  - Reproduction
    - Fertility rates by cohort (LUCITA)
  - Birth/death (LUCITA,SYPRIA)
  - Household division/agglomeration
  - Life cycle dynamics
    - Aging (LUCITA,SYPRIA)
    - Marriage (LUCITA)
    - Succession

IV. Land-use decision class (Figure 4)

1. *Land-use decision
  - *Agent decision model (function, (III.1) (SLUDGE,FEARLUS,LUCITA,SYPRIA)

  Data
  - Agent Internal and External characteristics (III.1) (FEARLUS,LUCITA,SYPRIA)
  - *Potential land uses (I.6) (SLUDGE,FEARLUS,LUCITA,SYPRIA)
  - Parcel accessibility (I.2) (SLUDGE,SYPRIA)
  - Neighbourhood effects (I.2) (SLUDGE,FEARLUS,SYPRIA)
  - Institutional rules and constraints
    - *Land-tenure rules (I.4) (SLUDGE,FEARLUS,LUCITA,SYPRIA)
    - Institutional interactions (SYPRIA)
  - Economic data values (I.5) (SLUDGE,FEARLUS,LUCITA,SYPRIA)
  - Biophysical suitability/capability (I.1, I.7, or II.1)
    - Varies by land use, externalities, and productivity (SLUDGE)
    - Spatially heterogeneous, constant over time (FEARLUS)
    - Expected yield (based on last obtained yield) (LUCITA)
    - Taken from biophysical succession, fertility and yield models (SYPRIA)

V. Land exchange class (Figure 5)

1. Suppliers of land
   - Motivation for supply
     - Profit
     - Out-migrating bankrupt agents (FEARLUS/ELMM,LUCITA)
     - Migration
     - Household dynamics
   - Parcels supplied
     - All parcels owned (FEARLUS,LUCITA)
   - Terms offered
     - No compensation required (SOME)
     - Minimum bid accepted (FEARLUS)

2. Acquirers of land
   - Motivation for acquiring land
     - SOME: Relative utility based on:
       - Parcel accessibility (I.2)
       - Neighbourhood effects (I.2)
       - Biophysical suitability/capability
     - Profit (FEARLUS,SYPRIA)
     - Migration (FEARLUS,LUCITA,SYPRIA)
     - Subsistence (SYPRIA)
     - Household dynamics
   - Parcels they hope to acquire
     - Random sub-sample (SOME)
     - Dependent on Land Parcel Purchasing decision strategy (FEARLUS)
     - Determined by distance to main road and nearest town (LUCITA)
     - Based on expected yield/profit (SYPRIA)
   - Terms offered
     - Based on expected profits (FEARLUS)

3. Exchange rules
   - Event sequencing/triggers for land transfers
     - In-migration (SOME,SYPRIA)
     - Out-migration (SYPRIA)
     - Profit expectation threshold
     - Bankruptcy (FEARLUS,LUCITA)
     - Death
   - Allocation mechanism
     - Agent occupies chosen parcel (SOME,LUCITA,SYPRIA)
     - Bidding mechanism
     - Auction (FEARLUS)
     - Negotiation
     - Bequest
     - Involuntary transfer

VI. Model operation class (Figure 6)

1. Model initialization
    - *Initial landscape structure (I.1) (SLUDGE,SOME,FEARLUS,LUCITA,SYRPIA)
    - Transport networks and initial accessibility/travel costs (I.2) (SLUDGE,SOME,SYRPIA)
    - Neighbourhood effects (I.2) (SLUDGE,SOME,FEARLUS,SYRPIA)
    - Non-spatial networks (I.3) (FEARLUS,SYRPIA)
    - *Institutional rules and constraints (I.4) (SLUDGE,SOME,FEARLUS,LUCITA,SYRPIA)
    - Economic data values (I.5) (SLUDGE,FEARLUS,LUCITA,SYRPIA)
    - Initial input from external biophysical and socioeconomic models (II) (LUCITA,SYRPIA)
    - *Agent types, numbers, and resource endowments (III) (SLUDGE,SOME,FEARLUS,LUCITA,SYRPIA)
    - Random seeds (FEARLUS)

2. Temporal Dynamics
    - *Number of iterations
        - Less than 20 (SLUDGE)
        - Variable, dependent on agent numbers to allocate (SOME)
        - Around 200 (FEARLUS)
        - 30 (LUCITA)
        - 10-40 (SYPRIA)
    - *Event Scheduling
        - Discrete time (synchronous or asynchronous) (SLUDGE,SOME,FEARLUS,FEARLUS,SYPRIA)
        - Discrete event (SYPIRA)