Using the ODD protocol for comparing three agent-based social simulation models of land use change

J. Gary Polhill[1], Dawn C. Parker[2], Daniel G. Brown[3], Volker Grimm[4]

[1] Macaulay Institute, Craigiebuckler, Aberdeen, AB15 8QH, United Kingdom, g.polhill@macaulay.ac.uk.

[2] Center for Social Complexity and Department of Environmental Science and Policy, George Mason University, MS 6B2, Fairfax, VA USA 22030, dparker3@gmu.edu.

[3] School of Natural Resources and Environment, 3505 Dana Building, University of Michigan, Ann Arbor, MI USA 48109-1041, danbrown@umich.edu.

[4] Helmholtz Centre for Environmental Research – UFZ, Department of Ecological Modelling, Permoserstr. 15, 04318 Leipzig, Germany, volker.grimm@ufz.de

Abstract

This article compares three agent-based social simulation models in the area of land use change using a model documentation protocol, ODD, from the ecological literature, with a view to examining how well it enables the models to be compared, how well fitted it is to social simulations, and how successful it might be in increasing communication between individual- and agent-based modellers. Such shared protocols can facilitate model review, comparison, and ultimately, replication. We initially conclude that the framework holds promise as a standard communication mechanism, although some refinements may be needed.

Keywords: Model communication, model comparison, model documentation, ODD, LUCC

1. Introduction

As agent-based social simulation matures as a domain of research, there are various attempts to make sense of the plethora of models, software, simulations, results, frameworks and libraries arising from it. In the area of Land Use and Cover Change (LUCC), members of the community met in 2001 at Irvine, California, in a workshop to compare agent-based models under development at the time. The resulting report (Parker, Berger, and Manson 2002) was possibly one of the first efforts to document and compare models variously termed under the headings MAS/LUCC, ABM/LUCC and ABLUMs, and a follow-up article (Parker, Manson, Janssen, Hoffmann and Deadman 2003) is one of the most popularly cited on the subject.

The LUCC report concludes with a set of questions that are relevant for literature in the field, defining potential criteria for referees and journal editors (p. 88):

> Is the author clear about the goals of the model? Are these goals appropriate? Has the model appropriately represented relevant spatial processes? Have standard techniques for verification and validation been used? Are the mechanisms of the model clearly communicated to the audience? Have the model mechanisms been appropriately verified? How does the model compare to other ongoing ABM/LUCC work?

These questions are as relevant today as they were five years ago. Unlike mathematical models, computer simulations have no standard language or protocol for communication (Grimm and Railsback 2005). A few mathematical equations and relevant derivations or conclusions from them can easily be included in a journal article, where they, and any implicit assumptions, are open to scrutiny by anyone fluent in mathematics. The equivalent in software is the source code of the simulation program, which may run into several hundred, if not thousands or tens of thousands of lines. These reams of material are hardly appropriate for inclusion in a journal article, and even if the source code is made available on the internet, the practicalities involved make their detailed scrutiny by the academic community unlikely. Yet any one line of code could embed a critical, possibly implicit, assumption (or even a mistake!) that might affect the acceptability of the model.

These issues are highlighted by those who report on reimplementation and replication work. Edmonds and Hales (2003) report that simply changing a `>=` in an `if` statement to a `>` in a model of Riolo, Cohen and Axelrod published in Nature (2001) dramatically reduces the effect emergent in their results. Galan and Izquierdo (2005) also show that changing arbitrary assumptions in one of Axelrod's (1986) models and running the simulation for longer generates the opposite results to those reported. Many authors undertaking replication work report that a great deal of communication between the original developers and those building the replication was necessary (Axtell, Axelrod, Epstein and Cohen, 1995; Bigbee, Cioffi-Revilla and Luke 2005), which further points to the inadequacy of model descriptions in the literature.

Though not all of these issues can be addressed in the literature itself, standards for documenting models in journal articles would at least ensure that all the relevant ground has been covered (Richiard, Leombruni, Saam and Sonnessa 2006). Together with links to further standardised supporting material elsewhere, it becomes possible to provide the kind of rigour and repeatability in simulation that a scientific endeavour ideally requires. To this end, Grimm et al. (2006) have proposed a standard protocol dubbed ODD (Overview, Design concepts, and Details) aimed at the description of individual based models in ecology, with a view to its application in agent-based social simulation and other disciplines. Though limitations of the approach are acknowledged (p. 124), it is perhaps more a case of refining rather than radically altering the protocol as it becomes more widely applied. Interestingly, much of the material that ODD stipulates be provided addresses the questions cited above in the LUCC report.

ODD was developed in large part by the individual-based modelling community for description of models produced by this community. Individual-based models differ from agent-based models in that they generally model non-human entities interacting within an ecological system (Grimm and Railsback 2005), whereas agent-based models generally model human actors and decisions (Gilbert and Troitzsch 2005). Part of the purpose of this paper is to assess the extent to which the ODD framework is sufficiently general to be of use to agent-based as well as individual-based modellers.

There are many reasons to work towards better communication and collaboration between these two groups of researchers, especially as far as models of land use and natural resource management are concerned. First, more and more models are being developed that focus on the interactions between human decision makers and non-human organisms (for example Dreyfus-Lyon and Klebe 2001; Harper, Westervelt, and Trame 2002; Mathevet, Bousquet, Le Page and Antona 2003). This means that individual- and agent-based modellers (I/ABM) have a strong motivation to develop an efficient means of communication. In particular, if a single framework can be developed that comprehensively describes both the individual- and agent-based components of the model, model description and communication is significantly simplified.

ODD makes no difference between individual- and agent-based models, because individual-based models in ecology are increasingly taking into account adaptive decisions of animals and plants (Railsback and Harvey 2002; Goss-Custard et al. 2006; Grimm, 2007). In fact, ODD can be used to describe any bottom-up simulation model, which also includes grid-based or cellular automaton models (Grimm et al. 2006). It remains, however, an open question whether the Design Concepts, which are part of the ODD protocol, and which obviously were formulated for organisms (e.g., fitness, adaptation, sensing) can also be used for human agents and problems from the social sciences. A common framework for describing adaptive agents in general would be desirable, because for example both ecological and economic models often focus on similar processes: competition for scarce resources, and on the evolution of successful strategies for resource acquisition. Many other concepts, such as fitness, increasing and diminishing returns, information gathering, expectation formation, and migration, are commonly investigated by both groups, suggesting the potential for sharing of model components.

Here, we consider the LUCC questions through applying ODD to three models in the ABM/LUCC literature: FEARLUS (Framework for Evaluation and Assessment of Regional Land Use Scenarios) (Polhill, Gotts and Law 2001; Gotts, Polhill and Law 2003) with the ELMM (Endogenised Land Market Model) extension (Polhill, Parker and Gotts 2005), SLUDGE (Simulated Land Use Dependent on eDGe Effect externalities) (Parker 1999; Parker and Meretsky, 2004; Parker 2005), and SOME (SLUCE's Original Model for Experimentation) (Brown and Robinson 2006; Rand et al. 2003; Brown, Page, Riolo, Zellner and Rand 2005; Brown, Page, Riolo and Rand 2004), with a two-fold purpose. First, we wish to examine how well-fitted ODD is to the description of these models. Second, we wish to explore how ODD facilitates their comparison. These questions are, however, addressed here only through the Overview and Design concepts part of ODD. After an introduction to the ODD protocol in section 2, we provide descriptions of the three models in section 3, and discuss our experience in using ODD in section 4 before concluding.

2. The ODD protocol

The ODD protocol is described in detail in Grimm et al. (2006). The following provides a brief overview, relating it to the LUCC report questions cited above. ODD stands for 'Overview, Design concepts and Details', which collectively comprise the three major categories of sections that ODD requires of a model description (Fig. 1). Of these sections, the Overview section is broken down into three subsections: 'Purpose', 'State variables and scales' and 'Process overview and scheduling'; and the Details section has subsections: 'Initialization', 'Input' and 'Submodels'. The Design concepts section is not subdivided, but provides a list of concepts that could be discussed.

The Overview section is intended to contain sufficient detail to create an outline of the model: the entities in the model (e.g., agents, collectives of agents, patches of the landscape), the processes, and the model's schedule? The 'Purpose' subsection is intended to explain what is to be done with the model, priming the reader's expectations for the ensuing model description. This clearly relates to the questions about the goals of the model in the LUCC report.

The 'State variables and scales' subsection outlines the structure of the model at a high level, but also at a low level, specifying *all* the variables that constitute the state of the model. Grimm et al. (2006) recommend the use of UML diagrams, particularly if the number of variables is large. The spatial (if applicable) and temporal scales addressed by the model are also contained in this subsection, with justifications. The 'Process overview and scheduling' subsection lists all the processes that occur in the model and how they are scheduled: who is doing what and when? The Overview section should thus allow readers to re-implement the skeleton of the model, i.e. the entities, or objects, including their state variables, the schedule, and the headers of the functions representing the processes. Collectively, the 'State variables and scales' and 'Process overview and scheduling' subsections relate back to the questions of adequate spatial representation and communication of mechanisms in the LUCC report.

Overview	**Purpose**
	State variables and scales
	Process overview and scheduling
Design concepts	**Design concepts**
Details	**Initialization**
	Input
	Submodels

Figure 1. The seven elements of the ODD protocol. The three categories on the left side are only for explaining the general structure of the protocol but are not used while describing a model. Rather, a model description following ODD has the seven sections listed on the right side. (After Grimm et al. 2006)

The Design concepts section does not describe the model itself, but the general concepts underlying its design. The model description is thereby linked to existing studies in the relevant literature, (addressing a similar question in the LUCC report). Suggested material to include in this section are: Emergence (a summary of emergent phenomena from the interaction of the agents), Adaptation (how the agents adapt their behaviour), Fitness/Objectives (a summary of the agents' goals), Prediction (how the agents predict the consequences of their decisions), Sensing (the environmental variables perceived by the agents, which might include their own variables), Interactions, Stochasticity (if present, and the reasons for it), Collectives (whether the agents are grouped socially) and Observation (how data are gathered from the model).

The Details section puts the flesh on the skeleton outlined in the Overview, and should enable complete re-implementation of the model. In some cases, the amount of information in this section could be too much to be included in a journal article, and would appear either in an appendix or a linked separate document. The 'Initialization' subsection describes how the model is bootstrapped, providing, if appropriate, references to any data used to give initial values to the state variables. The 'Input' subsection describes any other inputs to the model (such as time-series data of environmental variables). It may be necessary for this subsection to reference an online archive where the data and even the original random number seed can be accessed to achieve full reproducibility. (FEARLUS-G is a prototype grid-based environment for providing this kind of functionality for one particular model; Polhill, Pignotti, Gotts, Edwards and Preece in press.)

The ‘Submodels’ subsection explains in detail all the processes outlined in the ‘Process overview and scheduling’ subsection of the Overview. This includes describing how parameter values were chosen, and the testing and calibration of the submodels, which partly addresses the issues of verification and validation in the LUCC report, but only at the level of submodels. Model testing and validation at the level of the entire model are not part of ODD, because ODD is designed only to describe a model, not its analysis.

3. Three LUCC models

In describing the models, we adopt the convention that entities in the model (as opposed to the real world) are given an initial capital letter.

3.1. FEARLUS+ELMM

3.1.1. Purpose

FEARLUS was conceived out of the recognition that traditional spatial modelling techniques assuming (fiscally) economically rational behaviour could not always adequately account for observed spatial patterns. Land use change is therefore a complex process requiring integrated social, economic and biophysical models.

The FEARLUS software was developed with a deliberately modular architecture, to facilitate a broad range of land use change-related studies. We have therefore regarded FEARLUS as a modelling framework that can be configured to produce a particular model of interest, rather than a specific model in itself. Earlier work with FEARLUS involved comparing the relative success of innovating and imitating farmers. More recently, FEARLUS has been coupled with a water model (Koo, Dun and Ferrier 2004) to explore the potential influence of catchment-scale programmes of measures and social approval on diffuse pollution from land use (Davies et al. 2006), which includes the use of a government agent imposing fines or issuing rewards based on pollution targets for the catchment. For the purposes of this paper, we focus on describing FEARLUS for re-evaluating the relative success of innovating and imitating decision strategies for farmers when using a more realistic land market model (Polhill, Parker and Gotts 2005; Parker, Polhill and Gotts 2006). The specific question addressed by this work is whether more realistic land markets give a greater advantage to innovators than was suggested in the earlier work. The model will be referred to as FEARLUS+ELMM to distinguish it from FEARLUS as a framework.

3.1.2. State variables and scales

The FEARLUS+ELMM model consists of the following core entities, which are described in a series of tables. One time step in the model is a single Year.

Land Parcel: Field scale

Variable name	Brief description
Environment	The Environment this Land Parcel appears in (see below).
Biophysical Characteristics	A bitstring used to represent in an abstract way the local biophysical characteristics.

Land Use	A bitstring representing the land use this field has been applied to.
Yield	The Yield of the most recently applied Land Use.
Owner	The Land Manager responsible for making decisions for the Parcel, and harvesting the Yield from it.

Environment: Catchment or regional scale

Variable name	**Brief description**
Spatial Topology	Determines the neighbourhood of each Land Parcel (toroidal/bounded; von Neumann/Moore).
External Conditions	A bitstring representing spatially homogeneous conditions that change over time and affect Economic Returns to Land Managers.
External Conditions Flip Probability Array	Probability of each bit in the External Conditions changing from one Year to the next.
Biophysical Characteristics Clumped?	Whether or not to make the Biophysical Characteristics of neighbouring Land Parcels more similar to each other using a clumping algorithm.
Break-Even Threshold	The amount of Yield a Land Manager has to make from a Land Parcel to break even.
Land Uses	The set of Land Uses that Land Managers may apply to Land Parcels.

Land Manager: Farm scale

Variable name	**Brief description**
Land Parcel List	List of Land Parcels owned by the Land Manager.
Subpopulation	The Subpopulation this Land Manager belongs to, which determines the settings of its parameters.
Land Market	A pointer to the Land Market to which bids for Land Parcels should be sent.
Account	The accumulated wealth of the Land Manager.

Aspiration Threshold	The amount of Yield the Land Manager hopes to obtain from each Land Parcel.
Imitative Strategy	The algorithm to use for choosing a Land Use by imitating neighbouring Land Uses if the Aspiration Threshold is not achieved.
Memory size	How many Years in the past the Land Manager may look for data in the Imitative Strategy algorithm.
Innovative Strategy	The algorithm to use for choosing a Land Use without imitating neighbouring Land Uses if the Aspiration Threshold is not achieved.
Imitation Probability	The probability of choosing the Imitative Strategy if the Aspiration Threshold is not achieved.
Land Offer Threshold	The amount that must be in the Account before the Land Manager will bid for Land Parcels.
Bidding Strategy	The algorithm to use to generate a Price to offer for Land Parcels available for sale.
Selection Strategy	The algorithm to use to decide which bids for Land Parcels to actually make.

Subpopulation: Land Manager collective

Variable name	**Brief description**
Land Manager List	List of Land Managers belonging to this Subpopulation.
Incomer Offer Price Distribution	Determines the distribution from which new Land Managers of this Subpopulation will create an offer price for Land Parcels (e.g. Normal(Mean, Variance).
Imitative Probability Distribution	Distribution for the Imitative Probability of new Land Managers of this Subpopulation.
Aspiration Threshold Distribution	Distribution for the Aspiration Threshold of new Land Managers of this Subpopulation.
Land Offer Threshold Distribution	Distribution for the Land Offer Threshold of new Land Managers of this Subpopulation.

Bidding Strategy Configuration	Configuration string for the Bidding Strategy of new Land Managers of this Subpopulation. This depends on the particular Bidding Strategy algorithm used. For example, for a Wealth Multiple Bidding Strategy, this contains the distribution of the coefficient of the Account that member Land Managers will use to generate a bid from.

Land Market: Responsible for organising the exchange of Land Parcels among Land Managers.

Variable name	Brief description
Auction Type	First price sealed bid or Vickrey auction.

3.1.3. Process overview and scheduling

A high-level diagram showing an overview of the yearly schedule in FEARLUS is given in Fig. 2. More details on each section in the diagram is provided afterwards.

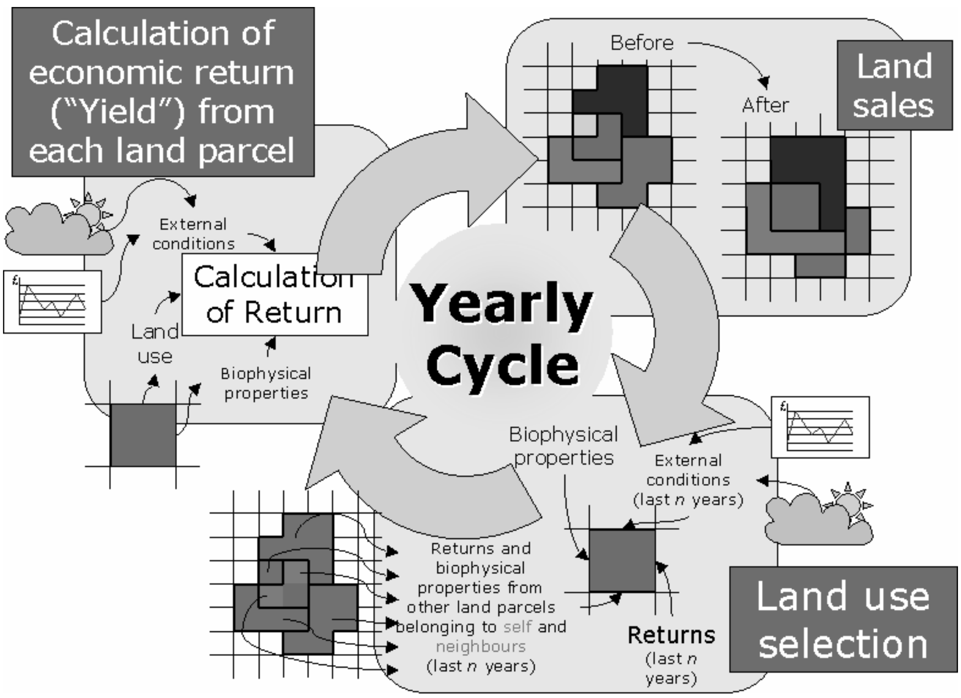

Figure 2. The Yearly cycle in FEARLUS. Starting at the bottom right, Land Managers choose Land Uses for their Land Parcels, the Economic Return is then calculated (top left), then Land Parcel exchanged (top right)

Land Use Selection

Land Managers do the following for each Land Parcel they own:

- If the Yield of the Land Parcel meets or exceeds the Aspiration Threshold of the Land Manager, then the Land Use is unchanged.

- If not, then if a random number in the range [0, 1] is less than the Imitative Probability, the Land Manager uses their Imitative Strategy to determine the new Land Use of the Land Parcel.
- Otherwise, the Land Manager uses their Innovative Strategy to determine a new Land Use of the Land Parcel

Examples of Imitative Strategies are:

- Choose a Land Use weighted by the number of times it occurs in the Land Manager's neighbourhood.
- Choose the Land Use having the highest mean Yield in the neighbourhood.

The Innovative Strategy is usually to choose uniformly randomly among the full set of Land Uses contained in the array in the Environment object.

Calculation of Return

The External Conditions bitstring is determined for this year. The Yield for each Land Parcel is then calculated, based on the number of matching bits in the concatenated External Conditions and Biophysical Characteristics bitstrings with the corresponding bits in the Land Use bitstring. Land Managers then increment their Account for each Land Parcel they own by the Yield minus the Break Even Threshold.

Land Sales

The Land Sales mechanism is discussed in detail in Polhill et al. (2005). Essentially, Land Managers must put all their Land Parcels up for sale if their Account is zero at the end of the Year. These Land Parcels are then bought by their neighbours, or by an in-migrating Land Manager. Neighbouring Land Managers use a Bidding Strategy to decide a *Bid* for each Land Parcel for sale. Examples would be to bid a certain proportion of the Account, to bid a proportion of the estimated Profit from the Land Parcel, or to bid a fixed price. A Selection Strategy is then used to decide which of the Bids they will actually make. An example would be to bid for the highest-priced Land Parcels first, as these are the Parcels of most value to the bidding Land Manager. A Subpopulation will also be selected at random to generate an in-migrant Bid for a Land Parcel for sale.

When the Land Allocator has received all the Bids, an auction is used to determine which of the Bids wins. The auction can be a first-price sealed-bid auction (ignoring the complication that it is not rational to bid your valuation in such an auction), or a Vickrey auction, in which the highest bidder wins, but the price paid is that of the second highest bid.

3.1.4. Design concepts

Emergence

The emergent effect we are interested in when using FEARLUS+ELMM for the purposes described in this paper is the performance of Land Managers employing different Land Use Selection Algorithms, i.e. with pure imitation or with innovating components (Imitation Probability = 1 or < 1, respectively). Currently, performance of Subpopulations is measured by comparing the numbers of Land Parcels owned by member Land Managers. Performance emerges from the interaction of the Land Managers with each other and the landscape. It can be influenced, but not entirely imposed, by the External Conditions Flip Probability Array and the Biophysical Characteristics Clumped? parameters.

Adaptation

Land Managers in FEARLUS adapt by choosing new Land Uses to respond to the changing External Conditions. Adaptive strategies are not directly aimed at making more money or acquiring more Land (the measures of fitness), but are instead heuristic. Thus, Random Experimentation could be seen as an effort to try anything new, whilst imitation could be seen as hoping that neighbours are making good choices of Land Use. Two forms of imitation have been tried: Simple Imitation, which chooses the modal Land Use in the neighbourhood, and Best Mean Imitation, which chooses the Land Use with the highest average Yield in the neighbourhood.

Land Managers also adapt by buying Land Parcels. More Land means that one poorly performing Land Parcel can be compensated for by another that performs well, and allows Land Managers to spread risk by diversifying the Land Uses employed.

Fitness

Fitness of individual Land Managers is determined by their Account. If the Account drops below zero, Land Managers are bankrupt, and no longer participate in the simulation. The fitness of a Subpopulation of Land Managers is determined by the number of Land Parcels they collectively own. The Account and the number of Land Parcels owned are related by the Land Market. Land Managers with more money are able to buy more Land.

Prediction

Prediction is implicit in heuristics used by some types of Land Managers. Simple Imitators assume that the most popular Land Use must be the best performing, whilst Best Mean Imitators use the average Yield as a proxy for estimated profit. Imitators are also implicitly assuming that successful Land Uses in the previous Memory Size Years are likely to be successful in the coming Year.

When the Yield from a Land Parcel meets the Land Manager’s Aspiration Threshold, the Land Use is retained on the Parcel from one Year into the next. Both innovators and imitators may do this, and it essentially entails the same assumption as above, but for the previous Year only.

Another implicit prediction is related to investment in a new Land Parcel. When Land is exchanged using a full Land Market, Land Managers use discounting to create a bid based on an estimated profit from the Parcel for sale that is a function of the Land Manager’s risk perception, the profit the Manager has made on other Parcels and the average Yield over the past n Years of the Parcel for sale (where n is a parameter in the Bidding Strategy Configuration).

Interaction

Imitating Land Managers interact with their neighbours to find out information about the performance of Land Uses in their area, i.e. from all Land Parcels owned by Land Managers owning a neighbouring Parcel. This set of Parcels is the ‘social neighbourhood’ of a Land Manager, and though the Parcels are queried directly, it is intended to represent Land Managers exchanging information.

All Land Managers also have mediated interaction in the Land Market, where they make competing bids for Land Parcels.

Sensing

Land Managers are assumed to have access to Yield, Land Use, External Conditions and Biophysical Characteristics data for all Land Parcels they make decisions for (including whether or not to buy them), and for imitating Land Managers, all neighbouring Land Parcels. Land Managers also know the state of their Account. Whether this information is used depends on the strategy employed. Simple Imitators just use Land Use information, while Best Mean Imitators use Yield information as well. In the Land Market, Land Managers use Yield and Account information when computing bids for Parcels using discounting.

Stochasticity

Stochasticity is used to simulate spatial variability in Land Parcels' Biophysical Characteristics, and temporal variability in External Conditions. Land Uses (see Section 3.1.2 above) are also initially randomly assembled. Clearly, stochasticity is involved in Random Experimentation for innovating Land Managers, and imitating Land Managers use stochasticity to select among Land Uses with equal maximum ordering (e.g. if two or more Land Uses are equally popular, Simple Imitators will select at random among them). In the Land Market, stochasticity is used to select a new owner for a Land Parcel with equal maximum bids from different Land Managers. If a simulation involves more than one Subpopulation, then the Subpopulation from which an in-migrant bid is generated for a Land Parcel for sale is selected at random.

Collectives

Subpopulations are collectives of Land Managers, represented explicitly with state variables used to create new Land Managers.

Observation

Various observations are available in FEARLUS+ELMM, from an omniscient perspective. However, the key observation as far as the work described herein is concerned is the number of Land Parcels owned by members of each Subpopulation at termination of the simulation.

3.2. SLUDGE

3.2.1. Purpose

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. Spatial externalities refer to land-use activities by one land owner that affect the payoffs to the land uses of surrounding neighbours. SLUDGE is an abstract model designed for theoretical exploration and hypothesis generation. Specifically, SLUDGE was designed to extent existing analytical microeconomic theory to examine relationships between externalities, market mechanisms, and the efficiency of free-market land use patterns. Effectively, the SLUDGE model functions as a search mechanism for a static equilibrium – one in which the current land-use pattern and composition are such that no agent has an incentive to choose a different land use.

3.2.2. State variables and scales

SLUDGE includes two types of entities: Land owners and market locations. Land owners are agents that occupy a single cell in a uniform cellular landscape. Since there is a 1:1 relation between a cell and its land owner, the state variable characterizing both of them are combined as the land owners variables.

Land owner:

Variable name	Brief description
Land use	Two types: zero or one.
Productivity	Land-use specific output variable
Externalities	Positive or negative productivity change with each neighbouring land use (4 variables)
Output	Sum of borders with cells in the same or the other land use times relevant externality. Externalities can influence productivity of a given land use.
Output Price 0	Parametric output price for output of land-use 0
Coordinates	X and Y coordinates of the cell, that determine, e.g., transportation costs to market locations.

Demand model:

Variable name	Brief description
Demand function	Downward-sloping function and scaling parameter that determines price of Output 1
Output Price 1	Realized price of Output 1 dependent on total supply

Market locations for the products of both land uses are specified by the user, and profits for each cell are reduced by transport costs to market via Euclidean distance.

Market location:

Variable name	Brief description
Coordinates	X and Y coordinates of the cell representing the market location for output of each land use
Transport costs	Land-use specific per-unit transport cost

The size of the cell-based landscape is also specified by the user *(Board_size)*. Thus, there is no absolute concept of spatial scale in the model (either extent or resolution). A relatively coarse resolution can be implemented by using a small landscape size and smaller demand parameter; and a relatively finer resolution model can be implemented through a larger landscape size and larger demand parameter. There is also no absolute concept of temporal scale since, as stated above, the model is effectively a search mechanism for a static equilibrium. The number of runs required to reach an equilibrium depends on the initial conditions of the model, but is usually less than 20.

3.2.3. Process overview and scheduling

Basically, SLUDGE considers only one process, the profit-maximisation decision for each land-owner agent on choosing land use zero or one. To make this decision, each agent first calculates an expected profit value for each of the two possible land uses, based on current landscape and market conditions. As described above, this value will depend on surrounding land uses and use-set parameters. To calculate an expected value for land use one, the agent must form an expected price for that land use. To form this expected price, the agent estimates a market supply curve, created by the reservation prices (price at which each land owner would convert to land-use one) for each agent, based on current landscape pattern. The agent estimates an expected price for land use zero by finding the intersection of this hypothetical supply curve with the parametrically set demand curve.

SLUDGE uses a fixed event-sequencing mechanism, which allows every other cell to make a land-use decision in each time period. This mechanism prevents oscillation, while introducing a minimal amount of additional path-dependency due to stochasticity. Agents are processed sequentially, but updating is synchronous, after each active agent has made a land-use decision. When each agent is active, they simply choose the land use that has the highest expected profit, choosing land use one if profits are identical.

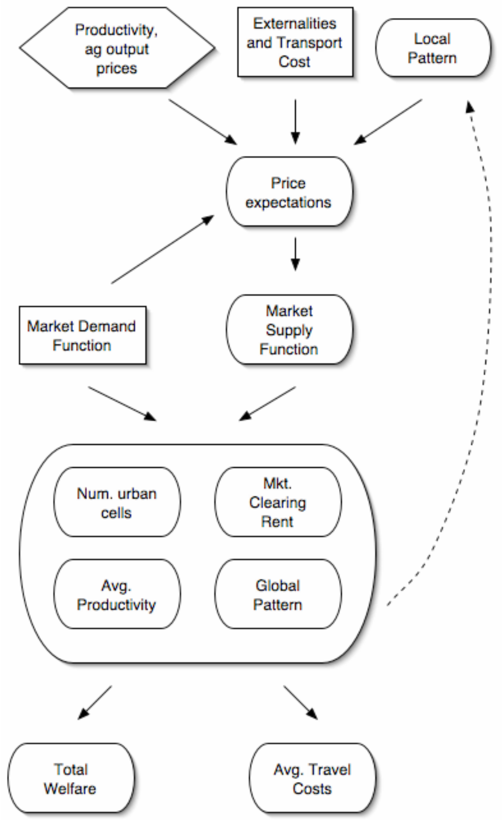

Figure 3: SLUDGE process overview (ovals are endogenous/emergent elements)

3.2.4. Design concepts

Emergence

SLUDGE was designed to explore the relationship between two related emergent phenomena: landscape pattern and economic value. The landscape patterns and associated landscape productivity measures are emergent in the sense that they are the result of the decentralised decisions of autonomous land-manager agents.

Adaptation

The SLUDGE model does not model adaptation, although extensions of the model that include adaptation could be designed. Possible real-world adaptations to reduced productivity from surrounding land uses could include innovation into new land uses, development of mitigation strategies, or development of strategic behaviour related to initial location and/or extent of land use.

Fitness

At an individual agent level, fitness is measured by the profitability of the managed land cell, and agents hold a goal of choosing the land use that maximizes their fitness. The individual does not consider its current state when making future decisions, and fitness measures are fixed over the life of the agent.

Prediction

SLUDGE agents predict future outcomes in only one simple way. They form an expected price for urban land by anticipating the fitness (profit) maximising decisions of other agents and the price that would result if other agents behaved optimally. In making this calculation, they are assumed to know the locations and profit functions of all other agents. They do not, however, anticipate the effects that these relocation decisions would have on their own fitness/profits more than one time period in advance. In this sense they are more myopic than real-world agents are likely to be. They have no memory or learning mechanisms.

Interaction

Agents interact indirectly at both a local and global level. At a local level, the land-use choice of one agent affects of the profits of its four local neighbours. At a global level, the agent's choice affects the returns to urban land.

Sensing

As mentioned in "prediction", agents are assumed to know the current landscape pattern and the profit-maximizing choices of other agents. Information is complete and certain.

Stochasticity

SLUDGE deliberately avoids introducing stochasticity in order to minimize path dependence in the model, especially as it was designed to extend other deterministic models. The only potential source of stochasticity is the ability of the end user to generate an initial random landscape, based on a proportion of cells of each type.

Observation

Observations include graphical display of land-use patterns, metrics measuring the fragmentation and productivity characteristics of the aggregate landscape, and metrics that reflect economic outputs (outputs from each land use, prices, transportation costs, and multiple economic fitness measures (producer surplus, consumer surplus, and total surplus). Global "fitness" is measured through economic welfare statistics, which depend on the degree of landscape fragmentation and market prices, as described above. One of the key roles of the SLUDGE model is to demonstrate that pursuit of fitness at the individual level will not necessarily maximize fitness at a global level.

3.3. SOME

3.3.1. Purpose

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 represented in residential agents, 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 2006), (2) the degree to which agent preferences in the model can produce patterns that approximate the power-law distribution of settled patch sizes observed in real cities (Rand et al. 2003), (3) path dependence in the patterns of urban settlement and their implications for the evaluation and validation of spatial patterns (Brown et al. 2005), (4) the role of zoning in constraining the possible patterns of city formation (Zellner et al. 2003), and (5) the effects of greenbelts a spreading urban pattern (Brown et al. 2004). Subsequent model development has led the group to expand the types of agents represented and the explicit effects of development on land cover. Given that the changes have led to a restructuring of the model, this expanded model has been given a new name (i.e., Dynamic Exurban Ecological Development, or DEED) and will be described in the literature as a different model. The description here focuses exclusively on the SOME model.

3.3.2. State variables and scales

SOME comprises a landscape consisting of cells and two agent types: Residents and Service Centres, both of whose primary behaviours are to locate themselves on a grid-based landscape following a location decision-making process. For use in the model all state variables are scaled into the range [0,1].

Landscape cells:

Variable name	**Brief description**
Coordinates	X and Y coordinates of the cell, that determine the Euclidean distance to Service Centres.
Aesthetic quality	A relative indicator of the aesthetic attractiveness of a cell to the residents.
Distance to Service Centres	The Euclidean distance to one or more service centres and scaled such that one is represents the shortest distance and 0 represents the longest distance observed at a given time step.
Neighbourhood Density	The number of cells occupied by residents or service centres within a neighbourhood around a given cell.
Neighbourhood Similarity	The similarity between the preference attributes of the already-located residents in the neighbourhood of a given location and those of the resident evaluating that location.

Residents:

Variable name	Brief description
Coordinates	X and Y coordinates of the cell where the Resident resides.
*Alpha (Aesthetic Quality)**	Relative importance to resident of Aesthetic Quality
Beta (Aesthetic Quality)	Preferred value of Aesthetic Value in the range
Alpha (Distance to Service Centres) *	Relative importance to resident of Distance to Service Centres
Beta (Distance to Service Centres)	Preferred value of Distance to Service Centres in the range
Alpha (Neighbourhood Density) *	Relative importance to resident of Neighbourhood Density
Beta (Neighbourhood Density)	Preferred value of Neighbourhood Density in the range
Alpha (Neighbourhood Similarity) *	Relative importance to resident of Neighbourhood Similarity
Beta (Neighbourhood Similarity)	Preferred value of Neighbourhood Similarity in the range
Utility	The overall level of satisfaction an agent receives from a locational choice.

*All alpha values are constrained to sum to one.

Service Centres:

Variable name	Brief description
Coordinates	X and Y coordinates of the cell where the Service Centre is located.

3.3.3. Process overview and scheduling

The following locational attributes are evaluated by the residents: aesthetic quality, distance to service centres, density, and neighbourhood similarity. All variables variable are updated and rescaled each time step or as needed when the underlying features change. Each time step, processes are scheduled in the following way:

```
For 1 to the defined number of residents to enter at each time step (specified by the user or file)
    Create a new Resident.
    For 1 to the number of locations to test
        Randomly select an unoccupied location (without replacement)
        Calculate Neighbourhood Similarity
        Evaluate Utility at that location
        If it is the first location then
            Store the Location and Utility as the best location.
        Else if it is not the first location evaluated by the resident then
            If the current location's Utility > best location's utility then
                Set the best Location and Utility to the current location
            End if
        End if
    Next Test Location
    Put Resident in the best location.
    Set Resident X,Y properties and utility values to those from the new location
    Calculate Neighbourhood Density for all cells
    If option is selected, update Aesthetic Quality near new resident

    If the total number of residents in the world divided by the specified number of residents per
        service centre minus the number of existing Service Centres is >= 1 then
        Select a random adjacent cell next to the last resident agent.
        Do until a location is selected for the Service Centre.
            To get a new location spiral outwards from the last resident location, while
                checking for edge effects.
            If the location is not occupied then
                Select the location.
            End if
        End Do
        Create a Service Centre
        Set Service Centre X,Y properties to those from the new location
        Calculate Distance to Service Centres for all cells
        If option is selected, update Aesthetic Quality near new service centre
    End IF
Next Resident
```

3.3.4. Design concepts

Emergence

SOME was designed to explore the processes that give rise to the spatial patterns of land settlement at the growing edge of a city, described in terms of their global and local properties, e.g., amount of development occurring at great distance from the city and clustering of developed patches. We have also evaluated distributions of utility achieved by residential agents. These patterns arise from the collective decisions of residential agents about where they wish to locate based on their preferences. While agents can have a preference for locating near service centres, and an initial service centre is seeded in the centre of the map in most applications, the patterns of service centres develop dynamically and, therefore, strong preference for nearness to service centres does not necessarily result in less sprawling development.

Adaptation

The SOME model includes adaptation only in the settlement process by choosing the best location for settlement in terms of utility. Extensions of the model that include more adaptation could be designed. For example, residents could adjust their preferences based on experience (i.e., where they settle initially) or the preferences of their neighbours (through a social learning process). Such adjustments could influence their calculations of utility or, if relocation were permitted in the model, subsequent location decisions.

Fitness

Each agent is assigned preferences when they are created and uses them to weigh alternative locations. In the current version of the model these preferences do not change during the course of the model run. The assignment is based on a random draw from a pre-defined distribution, intended to represent the distribution of preferences within the population.

Prediction

In SOME, the residential agents calculate utility based on the current state of the landscape. The predictions the agents make at the time they make their location decision, therefore, assume no change in the future. This is a form of tacit (and very naïve) prediction.

Interaction

Agents interact directly and indirectly. Indirect interactions involve the land-use choices of agents affecting the landscape characteristics that subsequent agents evaluate and the calculated utility of their neighbours. Agents interact directly when an incoming agent factors the preference characteristics of neighbouring residents into its determination of the utility it will get from a particular location. We assume that actual residents get clues about the preferences of their potential neighbours, when seeking a place to live, by looking at the aesthetic characteristics of their home and landscape.

Sensing

Agents are assumed to know perfectly the current landscape aesthetic quality, distance to services, neighbourhood similarity, and neighbourhood density of all locations they sample. However, their ability to sample locations is restricted by a parameter, which controls the incompleteness of information available about the housing market. They maximize the utility from among the choices available to them.

Stochasticity

SOME uses stochasticity to represent (a) the residential preferences of the agents (defined by predefined distributions), (b) patterns of aesthetic quality (in some applications), and (c) the location of the service centres after the first one (guided by the location of a resident).

Collectives

Two types of collectives exist within SOME. The first type is the categorization of locating agents as residents or service centres, which affects their behaviours. The second type, which affects only agent characteristics, involves, in some experiments, the identification of categories of residents that have their separate distributions from which preferences are drawn.

Observation

Observations include graphical display of land-use patterns, metrics measuring the sprawl and fragmentation of the settlement patterns, and metrics that describe distribution of achieved utility levels across the agent population.

4. Discussion

We applied the ODD protocol for describing individual- or agent-based models to three agent-based models of land-use change. The purpose of this exercise was to test whether ODD, which was formulated by ecologists who usually do not include human agents in their models, is also useful for agent-based models of the social sciences. So far, no final answer can be given to this question, although our exercise already revealed some benefits of the ODD protocol. Our exercise is somewhat limited by being restricted to the Overview and Design concepts parts of ODD (Fig. 1). These two parts should be, however, sufficient to communicate the basic structure of the model, its scales, processes, schedule, and how it was designed with regard to a suite of important concepts, for example emergence and fitness.

The three example models were first independently described according to ODD by those of use who were authors or co-authors of these models. The resulting descriptions were quite different and inconsistent, in particular the Overview parts. This problem has also been reported by Grimm et al. (2006) for the 19 model descriptions they used to test ODD for ecological models. We needed to revise our first descriptions and had to rely on the feedback and input of one of the developers of ODD (VG). ODD does thus not necessarily lead to consistent model descriptions per se, but requires active interactions with other users of ODD, or imitation of existing uses of ODD, which do not yet exist in social sciences. This current limitation of ODD was anticipated by Grimm et al. (2006, p. 124):

> Still, …, differences in the style of the presentation are likely to remain. We have to accept this at the current stage, because the protocol has to compromise between being general enough to include all kinds of individual- or agent-based models and being specific enough to fulfil its purpose.

For FEARLUS, one of the difficulties of using ODD was that the software itself was created with a view to conducting a broad range of studies, whilst ODD is focused on discussing the specific purposes for which a model has been built. This is understandable, since ODD is intended to apply to a specific piece of work with a model, though it does mean that there is a gap in terms of providing standards for documenting modelling frameworks such as FEARLUS as opposed to specific models.

Taxonomies are one potential approach to making descriptions of models more efficient. Hare and Deadman (2004) have made the first steps towards creating a taxonomy of land use change models, and Cioffi-Revilla and Gotts (2003) have defined the TRAP[2] class of models. These taxonomies may provide a shared vocabulary with which to describe our models, and thus may be an important first step towards a later goal the creation shared, standard programming libraries. Such approaches have the further advantage of not tying researchers down to any particular technology or programming language, whilst creating a basis to which models can be related more succinctly.

A related approach involves creation of a standard design patterns at the conceptual level, as per the MR POTATOHEAD framework created for agent-based models of land use change (Parker, Brown, Polhill, Deadman and Manson in press). ABM/LUCC models are perhaps particularly likely to have large numbers of state variables that collectively describe the system being modelled. These variables cover such things as the agents, the spatial topology and structure, the land cover, and the state of the biophysical system. It is possible that even this simplified description of the model will become unwieldy and too detailed to include in journal articles. However, many of the elements will be common, at least at a conceptual level, between different model implementations. The MR POTATOHEAD outlines these common elements in an object-oriented structure, with the goal of allowing users to trace out their own model as a special case of the common structure. It could therefore provide an effective additional means of documenting model details outside of the text of journal articles.

The MR POTATOHEAD framework was specifically created to enable the comparison of ABM/LUCC models. As such, its tailoring to a particular subset of models enables a more detailed comparison to be made than the more generally applicable ODD. The Overview part does enable some comparison: its intended use to develop the skeleton of the model allows such things as the properties of the spatial cells in the three models to be compared, as well as the properties and actions of the agents. However, the same level of detail in comparison that is achieved quite efficiently using MR POTATOHEAD would probably only be achieved through examining the 'Details' part of ODD, which would not typically be included in a journal article, but should be included in online archives of the corresponding journal, or in some future web repositories of ABMs

However, for communicating models to a new audience, less may be more as far as detail is concerned. Initial tests of MR POTATOHEAD as a mean of communication to scholars unfamiliar with the models indicated that this level of detail was overwhelming, and that a simpler overview may be more effective. Thus, the O and D parts of ODD may be more effective. In contrast to MR POTATOHEAD, ODD is more focused on communication and reimplementation. As such, we concurred that even the 'Overview' part of ODD provided better information for replication purposes. We also found the 'Design concepts' part useful because it puts considerably more structure on the information provided in the 'Purpose' section, giving the reader a much clearer impression of the motivation for the model. This is understandable, given that the intention of the 'Design concepts' section is at least in part to relate the model to other work in the literature (Railsback 2001; Grimm and Railsback 2005).

ODD does not follow the object-oriented paradigm, where the instance variables of model entities are described together with their processes. The reason for this with ODD was that the processes of an agent often would refer to other entities, which might not yet have been described, so that forward references would be necessary. It can be alternatively argued that object-oriented (OO) frameworks are more appropriate for description of I/ABMs. First, OO frameworks can be used to express hierarchical taxonomies, which can more effectively facilitate comparison between models, or expression of a series of models as special instances of a general class of models. At a more fundamental level, individual and agent-based models are by their nature focused on actions of autonomous entities. Thus, object-oriented programming (OOP) seems to be the most appropriate software design for I/ABMs (e.g., Grimm and Railsback 2005) because it allows creating object hierarchies and encapsulating properties of agents and what they do (their "methods") into one object.

On the other hand, ODD is not designed for model comparison but for communication, and ODD is also not necessarily related to the underlying software design. In fact, for using ODD it should not matter whether the model is implemented in JAVA, FORTRAN or NetLogo (the latter being a modern and powerful software platform for implementing ABMs that is not object-oriented). Tying OOD to the format of OOP at this early stage would limit its generality, and mix up software design and model description too much.

Nevertheless, OOP is an important concept, and a good compromise could be, as has been suggested by Grimm et al. (2006), that for those models that have been implemented using ODD, UML class diagrams could be used to communicate both the model entities' state variables and their processes in the same diagram. In ODD itself, the link between entities and processes is communicated in the schedule. Here, a general format still has to emerge, but a description of the schedule should not only include *what* is done at *what* time, but also *who* is doing it. A good example is given in Pitt et al. (2003), who use the schedule of their Swarm implementation to describe who is doing what at what time.

ODD was perceived as having a strong focus on “how” entities, processes, and schedules are implemented. ODD is more oriented towards model code than conceptual frameworks such as MR POTATOHEAD, and it was sometimes necessary to look back at code documentation to complete the ODD overview. This is surely a positive point of ODD, as one is made to think carefully about what is actually in the model, rather than relying on conceptual-level knowledge of its structure. There might be ways to combine the more general ODD, which has its focus on re-implementation, with MR POTATOHEAD, which is focussed on comparison of land-use models, combining the advantages of both approaches. For example, MR POTATOHEAD could be used as the “details” part, with some rearrangement. Then the state variables and process models could ask for basic descriptive overviews of specific items from MR POTATOHEAD.

Other efforts seeking to address the same issues as ODD besides those mentioned above include a number of normative calls for greater openness and integration in agent-based modelling (e.g. Alessa, Laituri and Barton 2006; Schweik, Evans and Grove 2005), and for development of tools to facilitate access to agent-based simulations (Polhill et al. in press). Another promising avenue of research is in the use of OWL ontologies (Antoniou and van Harmelen 2004) to describe agent-based models and agent-based modelling. Ontologies contain descriptions of key concepts and the relationships between them, together with restrictions on the relationships that allow the concepts to be defined such that automated reasoning services can infer concept membership and subsumption, and check the consistency of the ontology. Christley, Xiang and Madey (2004), for example, provide an ontology of agent-based modelling, whilst Polhill and Gotts (2006) illustrate how they could be used to link models to evidence and theory more explicitly, and Gotts and Polhill (2006) discuss their use as mediating formalisms between natural language and programming languages. Collectively these approaches begin to establish norms for best-practice in the field of agent-based social simulation, and opportunities for capitalising on their complementarities should be explored. It may also be that one protocol for model description will not fit all cases—if so, it will be necessary to establish criteria by which we can evaluate whether a particular protocol provides an adequate description, the ultimate test being that of reimplementation.

5. Conclusion

We conclude that already the parts of ODD that we tested (the Overview and Design Concepts) have its virtues and should further be considered for use with social simulation models. However, more and full applications of ODD are needed to better understand its specific potentials and limitations when dealing with models that include human agents. As more and more examples of ODD appear in the literature, it will be easier for others to follow the protocol without having the advice of its developers, and easier to see where changes are needed to clarify requirements, facilitate the model description process and fit the description needs of different models. We could confirm the status of ODD described in Grimm et al. (2006) as being the first step only on the way to establish a general protocol for describing individual- and agent-based models, though a nonetheless promising step. The success of ODD, MR POTATOHEAD, and similar approaches depends on them being used, scrutinized, and developed. For ODD, a forum for this is provided at via http://www.ufz.de/oesatools/odd.

6. Acknowledgements

This work was funded in part by the Scottish Executive Environment and Rural Affairs Department.

7. References

ALESSA L N, Laituri M and Barton M (2006) An “all hands” call to the social science community: Establishing a community framework for complexity modeling using agent based models and cyberinfrastructure. *Journal of Artificial Societies and Social Simulation* **9** (4). http://jasss.soc.surrey.ac.uk/9/4/6.html.

ANTONIOU G and van Harmelen F (2004). Web Ontology Language: OWL. In Staab S and Studer R (Eds.) *Handbook on Ontologies*. Berlin: Springer. pp. 67-92.

AXELROD R M (1986). An evolutionary approach to norms. *American Political Science Review*. **80** (4), 1095-1111.

AXTELL R, Axelrod R, Epstein J, and Cohen M D (1995). Aligning simulation models: A case study and results. *Computational and Mathematical Organization Theory* **1** (1), 123-141.

BIGBEE A, Cioffi-Revilla C and Luke S (2005). Replication of Sugarscape using MASON. In Troitzsch K G (Ed.) *Representing Social Reality: Pre-proceedings of the Third Conference of the European Social Simulation Association, Koblenz, September 5-9, 2005*. Koblenz: Verlag Dietmar Fölbach. pp. 6-15.

BOURDIEU P (1986). The forms of capital. In Richardson J (Ed.) *Handbook of Theory and Research for the Sociology of Education*. New York: Greenwood Press. pp. 241-258.

BROWN D G, Page S E, Riolo R and Rand W (2004) Agent based and analytical modeling to evaluate the effectiveness of greenbelts. *Environmental Modelling and Software* **19**, 1097-1109.

BROWN D G, Page S E, Riolo R, Zellner M and Rand W (2005) Path dependence and the validation of agent-based spatial models of land use. *International Journal of Geographic Information Systems* **19**, 153-174.

BROWN D G and Robinson D T (2006). Effects of heterogeneity in preferences on an agent-based model of urban sprawl. *Ecology and Society* **11** (1): 46, http://www.ecologyandsociety.org/vol11/iss1/art46/

CHRISTLEY S, Xiang X and Madey G (2004). Ontology for agent-based modeling and simulation. In Macal C M, Sallach D and North M J (Eds.) *Proceedings of the Agent 2004 Conference on Social Dynamics: Interaction, Reflexivity and Emergence, co-sponsored by Argonne National Laboratory and the University of Chicago, October 7-9*. http://www.agent2005.anl.gov/Agent2004.pdf

CIOFFI-REVILLA C and Gotts N (2003). Comparative analysis of agent-based simulations: Geosim and FEARLUS models. *Journal of Artificial Societies and Social Simulation* **6** (4). http://jasss.soc.surrey.ac.uk/6/4/10.html

DAVIES B, Koo B, Hunsberger C, Rothman D, Polhill G, Blackstock K, Izquierdo L, Gotts N, Ferrier R and Dunn S (2006). Story and simulation approaches to appraise possible programmes of measures for a sub basin in Scotland. *Third Harmoni-CA Forum and Conference, 5-7 April 2006, Osnabrück, Germany*. http://www.harmoni-ca.info/Conferences/Past_Meetings/3rd_Harmoni-CA_Forum_and_Conference/abstract%20Blackstock.pdf

DREYFUS-LEON M and P Kleibe (2001). A spatial individual behaviour-based model approach of the Yellowfin tuna fishery in the eastern Pacific Ocean. *Ecological Modelling* **146** (1-3), 47-56.

EDMONDS B and Hales D (2003). Replication, replication and replication: Some hard lessons from model alignment. *Journal of Artificial Societies and Social Simulation* **6** (4), http://jasss.soc.surrey.ac.uk/6/4/11.html.

FERNANDEZ L, Brown D G, Marans R and Nassauer J (2005). Characterizing location preferences in an exurban population: Implications for agent based modeling. *Environment and Planning B*, **32** (6), 799-820.

GALAN J M and Izquierdo L R (2005). Appearances can be deceiving: Lessons learned re-implementing Axelrod's 'Evolutionary Approach to Norms'. *Journal of Artificial Societies and Social Simulation* **8** (3), http://jasss.soc.surrey.ac.uk/8/3/2.html.

GILBERT N and K G Troitzsch (2005). *Simulation for the social scientist*. Open University Press.

GOSS-CUSTARD J D, Burton N H K, Clark N A, Ferns P N, McGrorty S, Reading C J, Rehfisch MM, Stillman R A, Townend I, West A D and Worrall D H (2006) Test of a behavior-based individual-based model: response of shorebird mortality to habitat loss. *Ecological Applications*, 16, 2215-2222.

GOTTS N M and Polhill J G (2006). Narrative scenarios, mediating formalisms, and the agent-based simulation of land use change. *EPOS 2006 Epistemological Perspectives on Simulation. II Edition, University of Brescia, Italy, October 5-6, 2006*. http://www.eco.unibs.it/epos/Papers/GottsPolhillEPOS2006Abstract.pdf

GOTTS N M, Polhill J G and Law A N R (2003). Aspiration levels in a land use simulation. *Cybernetics and Systems* **34**, 663-683.

GRIMM V (2007) Ecological models: Individual-based models. In Jørgensen S-E (Ed.) *Encyclopedia of Ecology*. Elsevier (in press).

GRIMM V, Berger U, Bastiansen F, Eliassen S, Ginot V, Giske J, Goss-Custard J, Grand T, Heinz S K, Huse G, Huth A, Jepsen J U, Jørgensen C, Mooij W M, Müller B, Pe'er G, Piou C, Railsback S F, Robbins A M, Robbins M M, Rossmanith E, Rüger N, Strand E, Souissi S, Stillman R A, Vabø R, Visser U and DeAngelis D L (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* **198** (1-2), 115-126.

GRIMM V and Railsback S F (2005) *Individual-based Modeling and Ecology*. Princeton University Press, Princeton, NJ.

HARE M and Deadman P J (2004). Further towards a taxonomy of agent based simulation models in environmental management. *Mathematics and Computers in Simulation* **64** (1), 25-40.

HARPER, S J, Westervelt J D and Trame A-M (2002). Management application of an agent-based model: control of cowbirds at the landscape scale. In Gimblett H R (Ed.) *Integrating Geographic Information Systems and Agent-Based Modeling Techniques for Understanding Social and Ecological Processes*. Oxford University Press.

KOO B K, Dunn S M and Ferrier R C (2004). A spatially-distributed conceptual model for reactive transport of phosphorus from diffuse sources: an object-orientated approach. *In Pahl-Wostl C, Schmidt S and Jakeman T (Eds.) IEMSs 2004 International Congress: Complexity and Integrated Resources Management, International Environmental Modelling and Software Society, Osnabrück, Germany, 14-17 June 2004*.

MARANS R W (2003). Understanding environmental quality through quality of life studies: The 2001 DAS and its use of subjective and objective indicators. *Landscape and Urban Planning* **65** (1-2), 75-85.

MATHEVET R, Bousquet F, Le Page C and Antona M (2003). Agent-based simulations of interactions between duck population, farming decisions and leasing of hunting rights in the Camargue (Southern France). Ecological Modelling 165: 107-126.

PARKER D C (1999). Landscape outcomes in a model of edge-effect externalities: A computational economics approach. *SFI Publication 99-07-051*. Santa Fe, NM: Santa Fe Institute. http://www.santafe.edu/sfi/publications/Working-Papers/99-07-051.pdf

PARKER D C (2005). Agent-based modelling to explore linkages between preferences for open space, fragmentation at the urban-rural fringe, and economic welfare. *Paper presented at The Role of Open Space and Green Amenities in the Residential Move from Cities, December 14-16 2005, Dijon, France*.

PARKER D C, Berger T and Manson S M (2002). Agent-Based Models of Land-Use and Land Cover Change: Report and review of an international workshop, October 4-7, 2001, Irvine, California, USA. *LUCC Report Series No. 6*. Anthropological Center for Training and Research on Global Environment Change, Indiana University, USA: LUCC Focus 1 Office.

PARKER D C, Brown D G, Polhill J G, Deadman P J and Manson S M (in press). Illustrating a new 'conceptual design pattern' for agent-based models of land use via five case studies—the MR POTATOHEAD framework. In Parades L and Iglesias C H (Eds.) *Agent-Based Modelling in Natural Resource Management*.

PARKER D C, Manson S M, Janssen M A, Hoffmann M J and Deadman P (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers* **93**, 314-337.

PARKER D C and Meretsky V (2004). Measuring pattern outcomes in an agent-based model of edge-effect externalities using spatial metrics. *Agriculture, Ecosystems and Environment* **101**, 233-250.

PARKER D C, Polhill J G and Gotts N M (2006). Do land markets matter? Preliminary results from the ELMM model. *Association of American Geographers Meeting "Perspectives on Geographic Complexity 2: Institutions, Markets and Policy." Chicago, Illinois, 7-11 March 2006*.

PITT W C, Box P W and Knowlton F F. 2003. An individual-based model of canid populations: modelling territoriality and social structure. *Ecological Modelling*, 166, 109-121.

POLHILL J G and Gotts N M (2006). A new approach to modelling frameworks. *Proceedings of the First World Congress on Social Simulation, August 21-25 2006, Kyoto University, Kyoto, Japan*. Vol 1., pp. 215-222.

POLHILL J G, Gotts N M and Law A N R (2001). Imitative versus nonimitative strategies in a land use simulation. *Cybernetics and Systems* **32** (1-2), 285-307.

POLHILL J G, Parker D C and Gotts N M (2005). Introducing land markets to and agent based models of land use change. In Troitzsch K G (Ed.) *Representing Social Reality: Pre-proceedings of the Third Conference of the European Social Simulation Association, Koblenz, September 5-9, 2005*. Koblenz: Verlag Dietmar Fölbach. pp.150-157.

POLHILL J G, Pignotti E, Gotts N M, Edwards P and Preece A (in press). A semantic grid service for experimentation with an agent-based model of land use change. *Journal of Artificial Societies and Social Simulation*.

RAILSBACK S F (2001). Concepts from complex adaptive systems as a framework for individual-based modelling. *Ecological Modelling*, 139, 47-62.

RAILSBACK S F and Harvey, B C (2002) Analysis of habitat selection rules using an individual-based model. *Ecology*, 83, 1817-1830.

RAND W, Brown D G, Page S E, Riolo R, Fernandez L E and Zellner M (2003). Statistical validation of spatial patterns in agent-based models. *Proceedings of Agent Based Simulation 4, Montpellier, France, 2003*.

RICHIARD M, R Leombruni R, Saam N and Sonnessa M (2006). A Common Protocol for Agent-Based Social Simulation. *Journal of Artificial Societies and Social Simulation* **9** (1). http://jasss.soc.surrey.ac.uk/9/1/15.html.

RIOLO R L, Cohen M D and Axelrod R (2001). Evolution of cooperation without reciprocity. *Nature* **411**, 441-443.

SCHWEIK C, Evans T and Grove J M (2005). Open source and open content: A framework for global collaboration in social-ecological research. *Ecology and Society* **10** (1): 33. http://www.ecologyandsociety.org/vol10/iss1/art33/

ZELLNER M L, Riolo R, Rand W, Page S E, Brown D G and Fernandez L E (2003). The interaction between zoning regulations and residential preferences as a driver of urban form. *2003 UTEP Distinguished Faculty and Student Symposium, Urban and Regional Planning Program, University of Michigan. April, 2003*.