The ODD protocol: a review and first update

[1]Volker Grimm[1], Uta Berger[2], Donald L. DeAngelis[3], J. Gary Polhill[4], Jarl Giske[5], Steven F. Railsback[6]

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

[2] Institute of Forest Growth and Computer Science, Dresden University of Technology, P.O. 1117, 01735 Tharandt, Germany

[3] USGS/Biological Resources Division and Dept. of Biology, University of Miami, PO Box 249118, Coral Gables, FL 33124, USA

[4] Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH, United Kingdom.

[5] University of Bergen, Department of Biology, P. O. Box 7803, N-5020 Bergen, Norway

[6] Department of Mathematics, Humboldt State University; and Lang, Railsback & Associates, 250 California Avenue, Arcata, California 95521, USA

Abstract

The 'ODD' (Overview, Design concepts, and Details) protocol was published in 2006 to standardize the published descriptions of individual-based and agent-based models (ABMs). The primary objectives of ODD are to make model descriptions more understandable and complete, thereby making ABMs less subject to criticism for being irreproducible. We have systematically evaluated existing uses of the ODD protocol and identified, as expected, parts of ODD needing improvement and clarification. Accordingly, we revise the definition of ODD to clarify aspects of the original version and thereby facilitate future standardization of ABM descriptions. We discuss frequently raised critiques in ODD but also two emerging, and unanticipated, benefits: ODD improves the rigorous formulation of models and helps make the theoretical foundations of large models more visible. Although the protocol was designed for ABMs, it can help with documenting any large, complex model, alleviating some general objections against such models.

Keywords: model description, model formulation, model replication, scientific communication, standardization

---

[1] Preprint of: Grimm V, Berger U, DeAngelis DL, Polhill G, Giske J, Railsback SF. 2010. The ODD protocol: a review and first update. *Ecological Modelling* 221: 2760-2768.

1 Introduction

Ecologists and social scientists have long been faced with the challenge of how to model the complexity inherent in many real-world ecological, social, or socio-ecological systems. One approach for exploring such systems is using agent-based models. (We hereafter refer to such models generically as ABMs, and use the terms 'individual' and 'agent' interchangeably.) ABMs focus on one or more of the following aspects because they are considered critical for explaining system-level behavior: heterogeneity of and among individuals, local interactions among individuals, and adaptive behavior of individuals (DeAngelis and Mooij, 2003, 2005; Grimm and Railsback, 2005).

ABMs were early criticized as generally being so poorly documented that the models could not be evaluated (e.g., Lorek and Sonnenschein, 1999). These criticisms motivated the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006), which attempted to create a generic format and a standard structure by which all ABMs could be documented. The primary purpose of ODD is to make writing and reading model descriptions easier and more efficient. Moreover, ODD is expected to lead to more complete model descriptions, making ABMs easier to replicate and hence less easily dismissed as unscientific.

In the few years it has existed, ODD has been used in more than 50 publications. ODD was also evaluated by using it to compare three different agent-based social simulation models of land-use change (Polhill et al., 2008), and was discussed and included in the portfolio of approaches fostered by the Open ABM Consortium, which was constituted in 2007 (Janssen et al., 2008). Hence a critical mass of experience has been reached, enabling the first update of the ODD protocol. This update was anticipated by Grimm et al. (2006, p. 116): "Once initiated, the protocol will hopefully evolve as it becomes used by a sufficiently large proportion of modelers." It was clear from the outset that the first version of a protocol designed to embrace the huge variety of ABM designs, complexity, scopes, or disciplines could not be optimal and that updates of the protocol would be needed.

Here we review the uses to date of ODD. This allows several observations to be made concerning the clarity and completeness of the protocol. An additional observation, however, was that the protocol has had unanticipated dividends that go beyond the expected practical benefits of providing a systematic documentation of models. That key benefit is that the protocol helps to promote a more rigorous formulation of models. The reason for this is that the ODD protocol provides a comprehensive checklist that covers virtually all of the key features that can characterize a model and that should be described. Because models are vehicles for applying theory to real world situations, we believe that this also helps communicate clearly the theoretical background and assumptions of the model.

A further observation is that the application of the ODD protocol to model descriptions may be appropriate not only for the ABMs, but for large, complex models in general. The advantages and disadvantages of large, complex models in ecology have been reviewed and debated in many places (e.g., Jørgensen, 1992; Liebhold, 1994; Logan, 1994; DeAngelis and Mooij, 2003; May, 2004; Grimm et al., 2005), the debate often revolving about the level of detail necessary in a model, the tradeoff being between greater realism on the one hand and greater parsimony and transparency on the other. It is not our goal to enter that debate, but to suggest that ODD be used as a thorough and consistent framework for documenting models, which can help to make large, complex models as clear as possible to the reader and user (e.g., Müller et al., 2007). If substantial clarification of large, complicated ecological models can be achieved, then a major disadvantage in such models, that is, the difficulty in understanding them, may be overcome. We will center our comments here on application to ABMs, but broader use of ODD is implied.

The update of the ODD protocol and its description is based on a review of all model descriptions using the protocol that existed by December 2009, checking whether the protocol's terminology was consistently understandable. This assessment had to be based on our subjective assessment on whether or not ODD elements were used as described in Grimm et al. (2006) because a more quantitative assessment seemed not to be possible at this stage.

Our main conclusion from three years of ODD application is that, while the protocol itself does not need a major overhaul, an update of the description of the protocol is needed, as several elements and some important terms have proven unclear or were sometimes misinterpreted. In addition, experience has revealed important potential benefits of ODD that were not foreseen when it was developed. It is worth addressing these benefits to further increase the value of the ODD protocol in the scientific community.

In the following, we first present our review of ODD-based model descriptions. As a result of this review, we then present an updated description and explanation of the seven elements of ODD. We then discuss those features of ODD that have been criticized as well as important benefits that were not anticipated by Grimm et al. (2006).

2 Review of ODD-based model descriptions

2.1 Methods

We searched the 'Web of Science' reference data base (Thomson Scientific) for publications citing the original ODD publication (Grimm et al., 2006). We selected those publications that claimed to follow the ODD protocol in the model descriptions. For each of the publications, we checked whether the ODD format was completely followed, which includes using exactly the identifiers and sequence of all seven elements of the ODD format. Then, for each of the elements of the protocol that was included, we checked whether it was either used more or less as described by Grimm et al. (2006), or whether an incorrect use could be directly referred to a weakness in the original ODD description, or whether parts of the protocol appeared to be inadequate in a given situation.

For the publications that included the 'Design concepts' element we recorded which design concepts were addressed; here, we included a design concept even if its qualifier, for example 'emergence', was not explicitly used, but information relevant to that qualifier was nonetheless supplied. We checked each of the publications for the discipline or field of research, whether the model was presented in the main manuscript or in an appendix, whether the schedules were described by using pseudo-code, diagrams, or other means, and whether tables with model parameters were included.

In addition to reviewing existing applications of the ODD protocol, we solicited direct feedback from ODD users, asking especially what they found suboptimal about the protocol. Most of this feedback was given verbally, or via e-mails, so that we cannot provide a solid database of feedbacks from ODD users; therefore, feedbacks are not included in the results section but in the discussion.

2.2 Results

By December 14, 2009, Web of Science listed 87 citations of Grimm et al. (2006). The ODD protocol was used in 54 of these publications; the other publications were reviews, addressing methods, or they just used Grimm et al. (2006) as a general reference to individual-based modeling. In 13 of the 87 publications (24%), one or more of the 28 authors of Grimm et al. (2006) were co-author. The majority of publications is from ecology (70% or 38 publications); other disciplines included behavioral sciences (six publications), epidemiology, forest science, social sciences (two publications each), and archeology, microbiology, biomedical research, and oceanography (one publication each).

Apart from 'Design concepts' and 'Input', the other elements of the ODD protocol were included in more than 80% of the ODD-based model descriptions (Fig. 1). The element 'Input' was included correctly in only 62% of the publications; in 13 cases (24%) 'Input' was omitted, and in 7 cases (13%) it was interpreted as model parameters instead of as input data of driving environmental variables imported from external files or models.

In 75% of the papers ODD was either followed completely and correctly, or only one of the seven elements was missing or was not used as described by Grimm et al. (2006). Six papers (11%) ignored the protocol's terminology or misinterpreted its intention by more than 50% (four or more elements omitted, labeled incorrectly, or misinterpreted).

Variation in the number of publications addressing design concepts was high (Fig. 2) and ranged between 93% (Stochasticity) and 7% (Prediction). If design concepts were addressed at all, often only three or four of the possible nine design concepts were included. 'Emergence', 'Stochasticity', and 'Observation' were used most often, whereas design concepts related to explicit models of adaptive behavior ('Adaptation', 'Fitness', 'Prediction') were listed in less than one third of the papers.

In 12 publications (22%) the entire model description, or parts of it, were presented in an appendix. In seven publications the description of the model's schedule was supported by presenting pseudo-code (12%), in 20 publications (37%) it was supported by diagrams, and in two cases it was supported by UML (Unified Modeling Language) diagrams. In 37 publications (69%) parameters were presented using a table. (The detailed evaluation sheet for all 54 ODD-based model descriptions is provided in the Supplementary Material.)

2.3 Discussion and Lessons

The high proportion of almost correct and complete uses of the ODD protocol (75%) shows that the protocol is of value to the scientific community. The protocol has proven to be applicable for a wide range of individual- and agent-based models from various disciplines. We conclude that major changes of the protocol regarding the number and sequence of its elements are not necessary. Figure 1 shows, however, that the description of the ODD elements should be improved. In the following we discuss in detail why each element was sometimes omitted, misunderstood, or renamed, and from this arrive at a modified and updated version of ODD, which is presented in the following section.

Purpose. – This element was never misunderstood but was omitted in some cases. This is probably because re-stating the purpose was considered redundant; usually, the purpose of the model was already stated in the introduction of a publication. The purpose of including this element should therefore be explained more clearly and it must be made clear that here only a very short, summary description of a model's purpose is required.

State variables and scales. – It seems that some authors had problems with the term 'state variables' (see also Polhill et al., 2008), because it seems to refer only to variables, or numbers, characterizing a physical or biological property of an agent. In many ABMs, however, agents are also distinguished by different behaviors or strategies, or by different values of certain model parameters; for example, all trees in an ABM might use the same sub-model describing growth, but trees of different species might be distinguished by different growth parameters. The description of this element thus needs to make clear that state variables can include behavioral attributes and model parameters. Moreover, since this element of ODD describes the structure of a model, speaking only of state variables but not of the entities characterized by the state variables, could be confusing. Therefore, it should be made clear that this ODD element is about the model's entities, their state variables (possibly including behavioral attributes and model parameters), and the model's spatial and temporal scales.

Process overview and scheduling. – Grimm et al. (2006) noted that most model descriptions do not include a description of the model's schedule that is detailed and precise enough to allow the model to be re-implemented. Still, in many ODD-based model descriptions, the schedule was not entirely clear. For example, often it is not specified in what sequence model entities are processed and when state variables are updated; this also applies to many of the figures used to visualize the schedule. We found schedule descriptions based on pseudo-code most useful. We conclude that the ODD protocol needs to describe more precisely what information this element should contain, and it should recommend using pseudo-code. It should also be made clear that in this ODD element processes are only listed, using the (self-explaining) names of their corresponding submodels, and except for very simple models, no details of the submodels should be presented here.

Design concepts. – This element was omitted in quite a few applications and, if it was included, often only very few concepts were addressed. One reason for this is probably that many ABMs do not include explicit submodels of adaptive behavior, so that none of the design concepts related to adaptive behavior apply. Another reason, however, is that the rationale of having design concepts included in the ODD protocol needs to be better explained. 'Fitness', one of the original design concepts, seems now to have been too narrow; a more general term, like 'objectives' is needed to make ODD more generally applicable. One concept essential to some ABMs, especially of human agents, is learning: whether and how agents change the rules or parameters governing behavior as a consequence of their experience. Learning is exactly the kind of concept that should be highlighted in this section, but the original protocol had no clear place for it.

At a more general level, independent of agent-based modeling, one or many basic principles are likely to underlie a model's design. In ecology, models can be based on basic principles, theory (Grimm, 1999), or general approaches, for example foraging theory, habitat selection, trophic interactions, trait-mediated interactions, etc. Similar basic principles exist in other disciplines. To better understand the design of an ABM (or any large, complex model) it should be explained how simple basic principles were taken into account in the design of a more realistic and mechanistically richer model. Therefore, basic principles should be included in the list of design concepts.

Initialization. – This element seems to be relatively clear. If it was omitted, then this was usually in papers that ignored most of the ODD elements anyway.

Input. – The name of this element was obviously confusing, since for many modelers 'input' refers to parameter values and sometimes also initial values of state variables. In the updated ODD, this element should be renamed to avoid this misunderstanding.

Submodels. – This element was usually named and used as intended by the ODD protocol. However, often the submodels' names and the names of the processes listed in process overview and scheduling did not match. Moreover, the clear separation between the factual description of a submodel; i.e., its equations, rules and algorithms, and explanations of its rationale, which is recommended by ODD, often did not exist. In the updated protocol, this has to be explained more clearly.

3 The ODD protocol: an updated definition

The following description and explanation of the seven elements of ODD is designed to fix the problems and ambiguities of the original protocol and its description. This updated ODD protocol fully replaces the original description given by Grimm et al. (2006), which is obsolete because of its ambiguities; however, the description of ODD's overall purpose and rationale given by Grimm et al. (2006) is still valid. The ODD protocol is defined by the seven elements described below, their labels or identifiers, and the sequence in which they are described. For clarification, a few identifiers have been renamed slightly and two design concepts have been added (Table 1).

Using ODD means using exactly these identifiers in the order specified by the protocol (numbering the elements, though, from 1 to 7 is optional and can depend on journal formatting requirements). There are manuscripts that claimed to follow the ODD protocol, but the order of elements was changed, elements were lumped, modified identifiers were used, or entire elements omitted. The purpose of a standard is, however, to assure a common understanding of the work done. Therefore it must be followed consistently.

When ODD is used, it should be referred to in the following way: "The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006; 2010[2])". This is important because when using a standard it is necessary to refer to where it has been described. Moreover, systematic evaluation of the practice of using ODD, as has been done in this review, would be impossible without references to the publications presenting ODD and its update.

In the following update of ODD, each element is described by questions providing a kind of checklist and explanations. A template document for writing ODD model descriptions that contains the following questions and explanations is included in the Supplementary Material.

1. Purpose

Question: What is the purpose of the model?

Explanation: Every model has to start from a clear question, problem, or hypothesis. Therefore, ODD starts with a concise summary of the overall objective(s) for which the model was developed. Do not describe anything about how the model works here, only what it is to be used for. We encourage authors to use this paragraph independently of any presentation of the purpose in the introduction of their article, since the ODD protocol should be complete and understandable by itself and not only in connection with the whole publication (as it is also the case for figures, tables and their legends). If one of the purposes

[2] This is a reference to this manuscript.

of a model is to expand from basic principles to richer representation of real-world scenarios, this should be stated explicitly.

2. Entities, state variables, and scales

Questions: What kinds of entities are in the model? By what state variables, or attributes, are these entities characterized? What are the temporal and spatial resolutions and extents of the model?

Explanation: An entity is a distinct or separate object or actor that behaves as a unit and may interact with other entities or be affected by external environmental factors. Its current state is characterized by its state variables or attributes. A state variable or attribute is a variable that distinguishes an entity from other entities of the same type or category, or traces how the entity changes over time. Examples are weight, sex, age, hormone level, social rank, spatial coordinates or which grid cell the entity is in, model parameters characterizing different types of agents (e.g., species), and behavioral strategies. The entities of an ABM are thus characterized by a set, or vector (Chambers, 1993; Huse et al., 2002), of attributes, which can contain both numerical variables and references to behavioral strategies.

One way to define entities and state variables is the following: if you want (as modelers often do) to stop the model and save it in its current state, so it can be re-started later in exactly the same state, what kinds of information must you save?

If state variables have units, they should be provided. State variables can change in the course of time (e.g. weight) or remain constant (e.g. sex, species-specific parameters, location of a non-mobile entity). State variables should be low level or elementary in the sense that they cannot be calculated from other state variables. For example, if farmers are represented by grid cells which have certain spatial coordinates, the distance of a farmer to a certain service centre would not be a state variable because it can be calculated from the farmer's and service centre's positions.

Most ABMs include the following types of entities:

- *Agents/individuals*. A model can have different types of agents; for example, wolves and sheep, and even different sub-types within the same type, for example different functional types of plants or different life stages of animals. Examples of types of agents include the following: organisms, humans, or institutions. Example state variables include: identity number (i.e., even if all other state variables would be the same, the agent would still maintain a unique identity), age, sex, location (which may just be the grid cell it occupies instead of coordinates), size, weight, energy reserves, signals of fitness, type of land use, political opinion, cell type, species-specific parameters describing, for example, growth rate and maximum age, memory (e.g., list of friends or quality of sites visited the previous 20 time steps), behavioral strategy, etc.

- *Spatial units (e.g., grid cells)*. Example state variables include the following: location, a list of agents in the cell, and descriptors of environmental conditions (elevation, vegetation cover, soil type, etc.) represented by the cell. In some ABMs, grid cells are used to represent agents: the state and behavior of trees, businesses, etc., that can be modeled as characteristics of a cell. Some overlap of roles can occur. For example, a grid cell may be an entity with its own variables (e.g., soil moisture content, soil nutrient concentration, etc., for a terrestrial cell), but may also function as a location, and hence an attribute, of an organism.

- *Environment*. While spatial units often represent environmental conditions that vary over space, this entity refers to the overall environment, or forces that drive the behavior and dynamics of all agents or grid cells. Examples of environmental variables are temperature, rainfall, market price and demand, fishing pressure, and tax regulations.

- *Collectives*. Groups of agents can have their own behaviors, so that it can make sense to distinguish them as entities; for example, social groups of animals, households of human agents, or organs consisting of cells. A collective is usually characterized by the list of its agents, and by specific actions that are only performed by the collective, not by their constitutive entities.

In describing spatial and temporal scales and extents (the amount of space and time represented in a simulation), it is important to specify what the model's units represent in reality. For example: "One time step represents one year and simulations were run for 100 years. One grid cell represents 1 ha and the model landscape comprised 1,000 x 1,000 ha; i.e., 10,000 square kilometers".

3. Process overview and scheduling

Questions: Who (i.e., what entity) does what, and in what order? When are state variables updated? How is time modeled, as discrete steps or as a continuum over which both continuous processes and discrete events can occur? Except for very simple schedules, one should use pseudo-code to describe the schedule in every detail, so that the model can be re-implemented from this code. Ideally, the pseudo-code corresponds fully to the actual code used in the program implementing the ABM.

Explanation: The "does what?" in the first question refers to the model's processes. In this ODD element only the self-explanatory names of the model's processes should be listed: 'update habitat', 'move', 'grow', 'buy', 'update plots', etc. These names are then the titles of the submodels that are described in the last ODD element, 'Submodels'. Processes are performed either by one of the model's entities (for example: 'move'), or by a higher-level controller that does things such as updating plots or writing output to files. To handle such higher-level processes, ABM software platforms like Swarm (Minar et al., 1996) and NetLogo (Wilensky, 1999) include the concept of the 'Model', or 'Observer', itself; that is, a controller object that performs such processes.

By "in what order?" we refer to both the order in which the different processes are executed and the order in which a process is performed by a set of agents. For example, feeding may be a process executed by all the animal agents in a model, but we must also specify the order in which the individual animals feed; that is, whether they feed in random order, or fixed order, or size-sorted order. Differences in such ordering can have a very large effect on model outputs (Bigbee et al., 2006; Caron-Lormier et al., 2008).

The question of when variables are updated includes the question of whether a state variable is immediately assigned a new value as soon as that value is calculated by a process (asynchronous updating), or whether the new value is stored until all agents have executed the process, and then all are updated at once (synchronous updating). Most ABMs represent time simply by using time steps: assuming that time moves forward in chunks. But time can be represented in other ways (Grimm and Railsback, 2005, Chapter 5). Defining a model's schedule includes stating how time is modeled, if it is not clear from the 'Entities, State Variables, and Scales' element.

4. Design concepts

Questions: There are eleven design concepts. Most of these were discussed extensively by Railsback (2001) and Grimm and Railsback (2005; Chapter. 5), and are summarized here via the following questions:

Basic principles. Which general concepts, theories, hypotheses, or modeling approaches are underlying the model's design? Explain the relationship between these basic principles, the complexity expanded in this model, and the purpose of the study. How were they taken into account? Are they used at the level of submodels (e.g., decisions on land use, or foraging theory), or is their scope the system level (e.g., intermediate disturbance hypotheses)? Will the model provide insights about the basic principles themselves, i.e. their scope, their usefulness in real-world scenarios, validation, or modification (Grimm, 1999)? Does the model use new, or previously developed, theory for agent traits from which system dynamics emerge (e.g., 'individual-based theory' as described by Grimm and Railsback [2005; Grimm et al., 2005])?

Emergence. What key results or outputs of the model are modeled as emerging from the adaptive traits, or behaviors, of individuals? In other words, *what* model results are expected to vary in complex and perhaps unpredictable ways when particular characteristics of individuals or their environment change? Are there other results that are more tightly imposed by model rules and hence less dependent on what individuals do, and hence 'built in' rather than emergent results?

Adaptation. What adaptive traits do the individuals have? What rules do they have for making decisions or changing behavior in response to changes in themselves or their environment? Do these traits explicitly seek to increase some measure of individual success regarding its objectives (e.g., "move to the cell providing fastest growth rate", where growth is assumed to be an indicator of success; see the next concept)? Or do they instead simply cause individuals to reproduce observed behaviors (e.g., "go uphill 70% of the time") that are implicitly assumed to indirectly convey success or fitness?

Objectives. If adaptive traits explicitly act to increase some measure of the individual's success at meeting some objective, what exactly is that objective and how is it measured? When individuals make decisions by ranking alternatives, what criteria do they use? Some synonyms for 'objectives' are 'fitness' for organisms assumed to have adaptive traits evolved to provide reproductive success, 'utility' for economic reward in social models or simply 'success criteria'. (Note that the objective of such agents as members of a team, social insects, organs—e.g., leaves—of an organism, or cells in a tissue, may not refer to themselves but to the team, colony or organism of which they are a part.)

Learning. Many individuals or agents (but also organizations and institutions) change their adaptive traits over time as a consequence of their experience? If so, how?

Prediction. Prediction is fundamental to successful decision-making; if an agent's adaptive traits or learning procedures are based on estimating future consequences of decisions, how do agents predict the future conditions (either environmental or internal) they will experience? If appropriate, what internal models are agents assumed to use to estimate future conditions or consequences of their decisions? What tacit or hidden predictions are implied in these internal model assumptions?

Sensing. What internal and environmental state variables are individuals assumed to sense and consider in their decisions? What state variables of which other individuals and entities can an individual perceive; for example, signals that another individual may intentionally or unintentionally send? Sensing is often assumed to be local, but can happen through networks or can even be assumed to be global (e.g., a forager on one site sensing the resource levels of all other sites it could move to). If agents sense each other through social networks, is the structure of the network imposed or emergent? Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?

Interaction. What kinds of interactions among agents are assumed? Are there direct interactions in which individuals encounter and affect others, or are interactions indirect, e.g., via competition for a mediating resource? If the interactions involve communication, how are such communications represented?

Stochasticity. What processes are modeled by assuming they are random or partly random? Is stochasticity used, for example, to reproduce variability in processes for which it is unimportant to model the actual causes of the variability? Is it used to cause model events or behaviors to occur with a specified frequency?

Collectives. Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Such collectives can be an important intermediate level of organization in an ABM; examples include social groups, fish schools and bird flocks, and human networks and organizations. How are collectives represented? Is a particular collective an emergent property of the individuals, such as a flock of birds that assembles as a result of individual behaviors, or is the collective simply a definition by the modeler, such as the set of individuals with certain properties, defined as a separate *kind* of entity with its own state variables and traits?

Observation. What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected? Are all output data freely used, or are only certain data sampled and used, to imitate what can be observed in an empirical study ("Virtual Ecologist" approach; Zurell et al., 2010)?

Explanation: The 'Design concepts' element of the ODD protocol does not describe the model *per se*; i.e., it is not needed to replicate a model. However, these design concepts tend to be characteristic of ABMs, though certainly not exclusively. They may also be crucial to interpreting the output of a model, and they are not described well via traditional model description techniques such as equations and flow charts. Therefore, they are included in ODD as a kind of checklist to make sure that important model design decisions are made consciously and that readers are aware of these decisions (Railsback, 2001; Grimm and Railsback, 2005). For example, almost all ABMs include some kinds of adaptive traits, but if these traits do not use an explicit objective measure the 'Objectives' and perhaps 'Prediction' concepts are not relevant (though many ABMs include hidden or implicit predictions). Also, many ABMs do not include learning or collectives. Unused concepts can be omitted in the ODD description.

There might be important concepts underlying the design of an ABM that are not included in the ODD protocol. If authors feel that it is important to understand a certain new concept to understand the design of their model, they should give it a short name, clearly announce it as a design concept not included in the ODD protocol, and present it at the end of the Design concepts element.

5. Initialization

Questions: What is the initial state of the model world, i.e., at time $t = 0$ of a simulation run? In detail, how many entities of what type are there initially, and what are the exact values of their state variables (or how were they set stochastically)? Is initialization always the same, or is it allowed to vary among simulations? Are the initial values chosen arbitrarily or based on data? References to those data should be provided.

Explanation: Model results cannot be accurately replicated unless the initial conditions are known. Different models, and different analyses using the same model, can of course depend quite differently on initial conditions. Sometimes the purpose of a model is to analyze consequences of its initial state, and other times modelers try hard to minimize the effect of initial conditions on results.

6. Input data

Question: Does the model use input from external sources such as data files or other models to represent processes that change over time?

Explanation: In models of real systems, dynamics are often driven in part by a time series of environmental variables, sometimes called external forcings; for example annual rainfall in semi-arid savannas (Jeltsch et al., 1996). "Driven" means that one or more state variables or processes are affected by how these environmental variables change over time, but these environmental variables are not themselves affected by the internal variables of the model. For example, rainfall may affect the soil moisture variable of grid cells and, therefore, how the recruitment and growth of trees change. Often it makes sense to use observed time series of environmental variables so that their statistical qualities (mean, variability, temporal autocorrelation, etc.) are realistic. Alternatively, external models can be used to generate input, e.g., a rainfall time series (Eisinger and Wiegand, 2008). Obviously, to replicate an ABM, any such input has to be specified and the data or models provided, if possible. (Publication of input data for some social simulations can be constrained by confidentiality considerations.) If a model does not use external data, this element should nevertheless be included, using the statement: "The model does not use input data to represent time-varying processes." Note that 'Input data' does *not* refer to parameter values or initial values of state variables.

7. Submodels

Questions: What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'? What are the model parameters, their dimensions, and reference values? How were submodels designed or chosen, and how were they parameterized and then tested?

Explanation: The submodels are presented in detail and completely. The factual description of the submodel, i.e., equation(s) and algorithms, should come first and be clearly separated from additional information. From what previous model this submodel was taken or whether a new submodel was formulated, and why, can be explained. If parameterization is not discussed outside the ODD description, it can be included here. The parameter definitions, units, and values used (if relevant) should be presented in tables.

Any description of an ABM and its submodels will seem ad hoc and lack credibility if there is no justification for why and how formulations were chosen or how new formulations were designed and tested. Because agent-based modeling is new and lacks a firm foundation of theory and established methods, we expect ODD descriptions to include appropriate levels of explanation and justification for the design decisions they illustrate, though this should not interfere with the primary aim of giving a concise and readable account of the model. Justification can be very brief in the Overview and Design concepts sections, but the complete description of submodels is likely to include references to relevant literature, as well as independent implementation, testing, calibration, and analysis of submodels.

ODD-based model descriptions consist of the seven elements described above; however, in most cases it will be necessary to have a simulation experiments or model analysis section following the model description (see Discussion).

4 Discussion

We have provided an updated ODD protocol for describing individual-based and agent-based models. Our updated description of ODD provides questions that can serve as a checklist for describing ABMs. We also renamed a few ODD elements to improve clarity, and added two design concepts: Basic principles and Learning.

In the following, we discuss both the three most frequently raised critiques in the protocol and emergent benefits which were not anticipated by Grimm et al. (2006).

4.1 Complaints about ODD

4.1.1 ODD can be redundant

Three elements of ODD were noted as being sources of redundancy: Purpose (likely to also be presented in a paper's introduction); Design concepts (included, more or less explicitly, in submodels' descriptions); and Submodels (because the submodels are also listed in Process Overview and Scheduling). We agree that there is some redundancy, but it is a price for the hierarchical structure of ODD, and it can be kept to an acceptable level. For example, redundancy in the Purpose element can be reduced by keeping this section very short. The redundancy associated with Design concepts often need not exist, because any details used in this element can then be left out of the Submodels element. The minor redundancy introduced by first providing the Process Overview and Schedule before all the submodel details is, in fact, needed to make sure that readers know and understand the context of each submodel. This is particularly appropriate if submodel details are published in an appendix or separately, which can be necessary for complex models (see Section 2.2).

4.1.2 ODD is overdone for simple models

Some ABMs are extremely simple, and describing them in ODD could use considerably more space than a complete description that does not use ODD. However, the benefits of using ODD are just as applicable to simple models, and it helps the reader understand what was left out to keep the model simple. The format of ODD can be shortened, when appropriate, such as by using continuous text instead of separate document subsections for each ODD element (see, for example, Jovani and Grimm 2008).

4.1.3 ODD separates units of object-oriented implementations

In object-oriented programming (OOP), model entities (i.e., agents) and their behaviors (i.e., processes and submodels) form one unit: objects with properties (state variables) and methods (processes). ODD, however, requires the properties and methods to be presented separately.

OOP is currently the natural platform for implementing ABMs (e.g., Grimm and Railsback, 2005), but OOP is not the only programming paradigm nor is it the last, and ODD was designed to be independent of software platforms. Moreover, the principle of encapsulation in OOP, which is designed to promote source code that is easier to maintain through collecting the data and methods that operate on them in one place, clearly does not necessarily apply for creating readable accounts of that code for humans.

Presenting entities first, describing them completely, and then describing what these entities can do, has the advantage that we first get a complete overview of what the model world *is*, before we learn how it can *change*. The link between entities and their processes is described in the model's schedule, where we specify who, i.e., what model entity, is performing a certain process or action. Readability is arguably improved through maintaining this separation.

Grimm et al. (2006) recommend using UML (Unified Modelling Language) class diagrams to graphically describe the model structure, but we refrain from this recommendation now, to make sure that ODD is independent of how models are implemented.

4.2 Emergent benefits of ODD

4.2.1 ODD promotes rigorous model formulation

Grimm et al. (2006) realized that we needed a way to communicate ABMs in a common format, because there was also no common, structured format for describing ABMs. But we found that once people develop experience using ODD to describe models, they start formulating new ABMs in the ODD format (Grimm 2008). The ODD protocol thus represents a natural and logical way to compose a model.

Starting with the formulation of the model's purpose, the next question to address is what entities should be in the model, and by what state variables or attributes those entities should be characterized. The next step is to consider what scales the model should use, what processes should be represented, and how the processes should be scheduled. The checklist of design concepts can then be used to decide such things as which processes should be imposed via empirical knowledge and fixed rates and probabilities, and which processes should emerge from adaptive behaviors. A detailed formulation for every submodel will then have to specified, often starting with extremely simple versions and increasing their sophistication, if needed, later on. (Decisions made throughout the modeling cycle [Grimm and Railsback, 2005] are likely to be iterative.) In so doing, it is necessary to think about what input data are needed and how to initialize the simulations.

It was the declared aim of ODD to increase readers' understanding of model descriptions by developing their expectations (sensu Gopen and Swan, 1990) of what information about a model is provided where and in what order. We are surprised by how strong these expectations are after using ODD for some time. There is thus a good chance that ODD will become fully established—used in most ABM publications—because once one starts using it, one very quickly gets used to it and considers it a natural and meaningful way to communicate and formulate ABMs or other complex models.

4.2.2 ODD facilitates reviews and comparisons of ABMs

Reviewing several ABMs that deal with a certain kind of problem or system is quite a task. To start, categories and criteria for classifying models must be identified, by itself a difficult task. If, however, the models are described in the ODD format, a review of their purpose, scales, structure, and process formulation is greatly simplified: one just puts the corresponding parts together in a table and scans for similarities and differences.

The first published review of ABMs that is based on ODD was a review of mangrove forest models (Berger et al., 2008). One important result of this review was that models initially perceived as fundamentally different turned out, when their basic structure design concepts were illuminated by ODD, to be unexpectedly similar (see also Polhill et al. 2008, Hellweger and Bucci 2009).

4.2.3 ODD may promote more holistic approaches to modeling and theory

In ecology, theory and modeling is currently transitioning from simple conceptual and idealized mathematical models derived from, e.g., Life History Theory (Murdoch 1966, Williams 1966) and Optimal Foraging Theory (Emlen 1966, MacArthur & Pianka 1966) to approaches that combine ecology with physiology and psychology, to incorporate underlying mechanisms of phenomena at the ecological level (e.g. Gilmour & al. 2005, White & al. 2007, McNamara & Houston 2009, Dingemanse & al. 2010, Pravosudov & Smulders 2010). Models of these phenomena are unavoidably becoming more complex, often requiring the use of ABMs. As complex models become the rule in bridging the biological, and similarly the social sciences, stringent protocols are needed to ensure communication between disciplines.

Clear communication of models should also be clear communication of theory. Theoretical considerations underlie all models, but in large models the theoretical foundations may be lost. We suggested above that Design concepts are augmented by 'Basic principles' to include what the modelers see as the theory motivating their models. Models should be the means by which general theoretical concepts and equations are given specific forms to apply to the real world.

Our impression is that one of the greatest problems of ecology (and perhaps also in social sciences) as a science is that ecological theory is highly scattered and not always clearly articulated in models. This is especially obvious when several clusters of theory are gathered in an ABM or other large model. The ODD protocol is one way to allow the theoretical aspects of these models to be articulated more clearly, and also for the important theory gaps to be visible. Wide use of the updated ODD protocol would thus facilitate approaches and theory which are holistic in the sense that they link levels of organization, different case studies, and possibly even different disciplines.

4.3 Limitations and outlook

One inherent limitation of ODD is that it is designed to describe a definite model version, whereas we often have to compare different versions to identify the best among alternative submodels, or to learn about the significance of different model designs, assumptions, and parameterizations. However, a focused model analysis requires a reference. We therefore recommend, as did Grimm et al. (2006), to broaden the reference ODD of a model by a separate section in the Materials and Methods section called Simulation Experiments or Model Analysis.

A similar problem is that different publications are often based on different versions of the same model, with only a few of the models entities or processes changed. For such cases, it would be convenient to have a Δ-ODD that describes only the differences from a reference version of the model. A Δ-ODD might be possible and useful, but in the meantime we still recommend that a full ODD description be provided (often, in an appendix) for each published version.

An inherent limitation of our review and update is that the usefulness of a proposed standard – ODD – was assessed by some of those who originally proposed this protocol (or tested it for the social sciences). Independent and more quantitative tests would be preferable and we hope to see them in the future. For example, ODD's usefulness for making models replicable could be tested by comparing replications of ODD-based and other model descriptions. The ultimate test, though, of ODD's usefulness and potential for becoming "the" standard for describing ABMs (and possibly other types of large, complex models) is how widely ODD will be used in the future. Within only six months – between our evaluation of the literature and writing this (July 26, 2010) – the number of citations of the original ODD paper increased from 87 to 123, which we take as an indicator for the increasing, and to some degree self-reinforcing use of ODD as a standard format.

None of the ODD initiators were entirely convinced by ODD's benefits in the beginning. Their opinions improved while using the protocol for their own model descriptions and, more often, while using it as a tool for model development during teaching agent-based modeling. It is also valuable for those faced with reviewing and reading modeling articles, who are otherwise faced with ad hoc descriptions of models that are often difficult to follow and incomplete. Our study of articles using ODD so far has shown that an update to the protocol is timely. We hope that this contribution will stimulate further researchers to try it, and offer feedback on how it may be further refined.

Acknowledgements

We would like to thank two anonymous reviewers for comments on an earlier draft and all those who provided feedback on the ODD protocol, in particular: Thomas Banitz, Dan Brown, Jürgen Groeneveld, Jean Le Fur, Roger Jovani, Martin Köchy, Dawn Parker, Cyril Piou, Eva Roßmanith, Nadja Rüger, Gillian Salerno and Amelie Schmolke. DLD was supported by the Biological Resources Division of the U. S. Geological Survey, JGP was supported by funds from the Scottish Government Rural and Environment Research and Analysis Directorate.

References

Berger, U., Rivera-Monroy,V., Doyle, T.W., Dahdou-Guebas,F., Duke, N.C., Fontalvo-Herazo, M., Hildenbrandt, H., Koedam, N., Mehlig, U., Piou, C., Twilley, R.R., 2008. Advances and limitations of individual-based models to analyze and predict dynamics of mangrove forests. Aquatic Botany 89, 260-274

Bigbee, T., Cioffi-Revilla, C., Luke S., 2006. Replicating the classic Sugarscape in MASON. In: Complex Behavior in Economics: Modeling, Computing and Mastering Complexity. Third Aix en Provence Complexity Workshop (COMPLEXITY2006), Aix-en-Provence, France, 17-21 May 2006. http://www.vcharite.univ-mrs.fr/conferences/

Caron-Lormier, G., Humphry, R.W., Bohan, D.A., Hawes, C., Thorbek, P., 2008. Asynchronous and synchronous updating in individual-based models. Ecol. Modell., 212, 522-527.

Chambers, R.C., 1993. Phenotypic variability in fish populations and its representation in individual-based models. Transactions of the American Fisheries Society 122, 404-414

DeAngelis, D.L., Mooij, W.M., 2003. In praise of mechanistically-rich models. In: Canham, C.D., Cole, J.J., Lauenroth, W.K., Eds., Models in Ecosystem Science. Princeton University Press, Princeton, New Jersey, pp. 63-82.

DeAngelis, D.L., Mooij, W.M., 2005. Individual-based modeling of ecological and evolutionary processes. Ann. Rev. Ecol. Syst. 36, 147-168.

Dingemanse, N.J., Kazem, A.J.N., Reale, D., Wright, W., 2010. Behavioural reaction norms: animal personality meets individual plasticity. Trends in Ecology and Evolution 25, 81-89

Eisinger, D., Wiegand, K., 2008. SERGE: A spatially explicit generator of local rainfall in southern Africa. South African Journal of Science 104, 37-42.

Emlen, J.M. 1966. The role of time and energy in food preference. Am. Nat. 100, 611-617.

Gilmour, K.M., Wilson, R.W., Sloman, K.A., 2005. The integration of behaviour into comparative physiology. Physiological and Biochemical Zoology 78, 669-678.

Gopen, G. D., Swan, J. A., 1990. The science of scientific writing. American Scientist 78, 550-558.

Grimm, V., 1999. Ten years of individual-based modelling in ecology: what have we learned, and what could we learn in the future? Ecological Modelling 115, 129-148.

Grimm V., 2008. Individual-based models. In: Jørgensen, S.E., Fath, B.D., Eds., Ecological Models, Vol. [3] of Encyclopedia of Ecology, 5 vols. Elsevier, Oxford, pp. 1959-1968.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S., 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., DeAngelis, D. L., 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, 115-126.

Grimm, V., Railsback, S. F., 2005. Individual-Based Modeling and Ecology. Princeton University Press, Princeton.

Grimm, V, Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., Thulke, H.-H.,. Weiner, J, Wiegand, T., DeAngelis, D. L., 2005. Pattern-oriented modeling of agent-based complex systems: lessons from ecology. Science 310, 987-991.

Hellweger F.L., Bucci V., 2009. A bunch of tiny individuals - individual-based modeling for microbes. Ecological Modelling 220, 8-22

Huse, G., Giske, J., Salvanes, A.G.V., 2002. Individual-based modelling. In: Hart, P.J.B., Reynolds, J.D., Eds., Handbook of Fish and Fisheries. Blackwell Science, Oxford, pp. 228-248.

Janssen, M.A.., Alessa, L.N., Barton, M., Bergin, S., Lee, A., 2008. Towards a community framework for agent-based modelling. Journal of Artificial Societies and Social Simulation 11(2)6 <http://jasss.soc.surrey.ac.uk/11/2/6.html>

Jeltsch, F., Milton, S. J., Dean, W. R. J., van Rooyen, N., 1996. Tree spacing and coexistence in semiarid savannas. Journal of Ecology 84, 583-595.

Jørgensen, S. E., 1992. Integration of Ecosystem Theories: a Pattern. Kluwer Academic Publishers.

Jovani, R., Grimm, V., 2008. Breeding synchrony of colonial birds: from local stress to global harmony. Proceedings of the Royal Society London B 275, 1557-1563.

Liebhold, A. M., 1994. Use and abuse of insect and disease models in forest pest management; past, present, and future. In: Covington, W.W. DeBano, L.F., Eds., Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management. U. S. Dept. Agric. Forest Service Tech. Report RM-247, pp. 204-210.

Logan, J. A., 1995. In defense of big ugly models. American Entomologist 40, 202-207.

Lorek, H., Sonnenschein, M., 1999. Modelling and simulation software to support individual-oriented ecological modelling. Ecol.Model. 115, 199-216.

MacArthur, R.H., Pianka, E.R., 1966. On optimal use of a patchy environment. American Naturalist 100, 603-609.

May, R. M., 2004. The uses and abuses of models in biology. Science 303, 790-793.

McNamara, J.M., Houston, M.I., 2009. Integrating function and mechanism. Trends in Ecology and Evolution 24, 670-675.

Minar, N., Burkhart, R., Langton, C., Askenazi, M., 1996. The Swarm simulation system: a toolkit for building multi-agent simulations. Tech. rept., Santa Fe Institute, Santa Fe, NM.

Müller, B., Linstädter, A., Frank, K., Bollig, M., Wissel, C., 2007. Learning from local knowledge: modeling the pastoral-nomadic range management of the Himba, Namibia. Ecological Applications 17, 1857-1875, 2007.

Murdoch, W.W., 1966. Population stability and life history phenomena. Am. Nat. 100, 5-11.

Polhill, J. G., Parker, D. C., Brown, D. G., Grimm, V., 2008. Using the ODD protocol for describing three agent-based social simulation models of land use change. Journal of Artificial Societies and Social Simulation 11(2): 3, http://jasss.soc.surrey.ac.uk/11/-2/3.html.

Pravosudov, V.V., Smulders, T.V., 2010. Integrating ecology, psychology and neurobiology within a food-hoarding paradigm. Phil. Trans. R. Soc. B 2010 365, 859-867

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

White, D.W., Dill, L.M., Crawford, C.B., 2007. A common, conceptual framework for behavioral ecology and evolutionary psychology. Evolutionary Phychology 5, 275-288.

Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo. Center for Connected Learning and Computer-Based Modeling. Northwestern University, Evanston, IL.

Williams, G.C., 1966. Natural selection, the cost of reproduction, and a refinement of Lack's principle. Am. Nat. 100, 687-690

Zurell, D., Berger, U., Cabral, J.S., Jeltsch, F., Meynard, C.N., Münkemüller, T., Nehrbass, N., Pagel, J., Reineking, B., Schröder, B., Grimm, V., 2010. The virtual ecologist approach: simulating data and observers. Oikos 119, 22-635.

Tables

Table 1. The seven elements of the original and updated ODD protocol. The names of two elements was modified (elements 2 and 6), one design concept was renamed (from Fitness to Objectives, and two design concepts were added (Basic principles and Learning). Numbering the seven elements when using the protocol is optional. The elements can be grouped in three categories (Overview, Design concepts, Details; hence: ODD), but these categories are not meant to be included when using the ODD protocol.

	Elements of the original ODD protocol (Grimm et al. 2006)	Elements of the updated ODD protocol
Over view	1. Purpose	1. Purpose
	2. State variables and scales	2. Entities, state variables, and scales
	3. Process overview and scheduling	3. Process overview and scheduling
Design concepts	4. Design concepts • Emergence • Adaptation • Fitness • Prediction • Sensing • Interaction • Stochasticity • Collectives • Observation	4. Design concepts • Basic principles • Emergence • Adaptation • Objectives • Learning • Prediction • Sensing • Interaction • Stochasticity • Collectives • Observation
Detail s	5. Initilization	5. Initialization
	6. Input	6. Input data
	7. Submodels	7. Submodels

Figure Captions

Figure 1. Percentages of publications using the ODD protocol (n=54) for describing an individual-based or agent-based model that include each of the seven elements described by Grimm et al. (2006), i.e. Purpose, State variables and scales, etc. Black: the element was named and used as described in Grimm et al. (2006); dark gray: the element was included and named correctly, but misinterpreted; light gray: the element was omitted or labeled incorrectly.

Figure 2. From the 43 publications that included the element 'Design concepts', the percentage of publications that address a certain design concept.

Figure 1

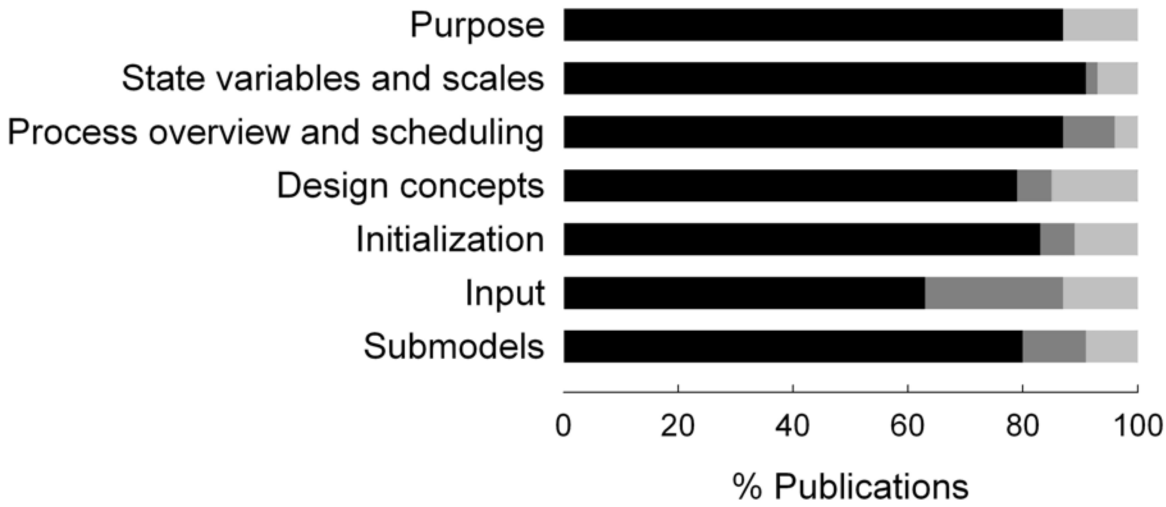
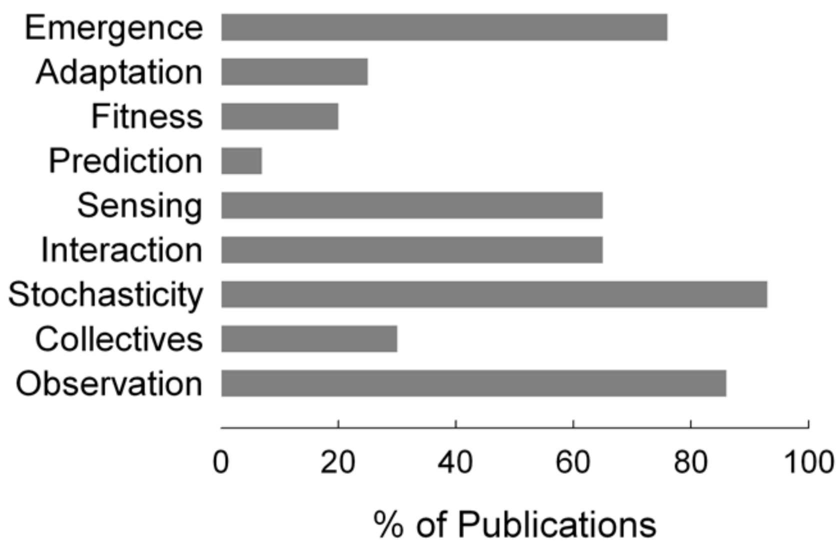


Figure 2



Supplement 1

Table S1. Evaluation of 54 publications that use the ODD protocol for describing an individual- or agent-based model. (See text for further explanations).

	Reference	Purpose	State	Process	Design concepts	Inititialization	Input	Submodels	Discipline	MS /Appendix	Scheduling	Paramtert table
1	Banitz T, Huth A, Grimm V, Johst K (2008) Clumped versus scattered: how does the spatial correlation of disturbance events affect biodiversity? *Theoretical Ecology* 1: 231-240	OK[3]	OK	OK	[4]Stoch, observ	OK	OK	OK	Ecol	MS[5]	Pseu[6]	Y
2	Beaudouin R, Monod G, Ginot V (2008) Selecting parameters for calibration via sensitivity analysis: An indlividual-based model of mosquitofish population dynamics. *Ecological Modelling* 218: 29-48	OK	OK	OK	Stoch, observ	OK	OK	OK	Ecol	MS	Pseu	Y
3	Best EPH, Boyd WA (2008) A carbon flow-based modelling approach to ecophysiological processes and biomass dynamics of Vallisneria americana, with applications to temperate and tropical water bodies. *Ecological Modelling* 217: 117-131	-[7]	-	-	-	-	-	-	Ecol	-	Flow	-

[3] OK: The element is included in the model description using exactly the label required by the ODD protocol and largely following the protocol intentions.

[4] Design concepts: emerge: Emergence; adapt: Adaptation; inter: Interaction; sense: Sensing; stoch: Stochasticity; observ: Observation; collect: Collectives; fit: Fitness; predict: Prediction. Design concepts in brackets: the concept was described without using the concepts name, or a new concept was introduced.

[5] MS: The full model description is included in the manuscript

[6] Pseu: Pseudocode

[7] - : The element is omitted or using a modified label.

4	Bithell M, Brasington J (2009) Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution. *Environmental Modelling & Software* 24: 173-190	OK	OK	OK	No[8]	OK	OK	OK	Fores	AP[9]	UML[10]	N
5	Blaum N, Wichmann MC (2007) Short-term transformation of matrix into hospitable habitat facilitates gene flow and mitigates fragmentation. *Journal of Animal Ecology* 76: 1116-1127	OK	OK	OK	Emerge, adapt, inter, sense, stoch, collect, observe	OK	OK	OK	Ecol	AP	Txt[11]	Y
6	Brochier T, Lett C, Tam J, Freon P, Colas F, Ayon P (2008) An individual-based model study of anchovy early life history in the northern Humboldt Current system. *Progress in Oceanography* 79: 313-325	OK	OK	OK	Stoch, observ	OK	-	OK	Ocea	Ms	Txt	No
7	Caplat P, Anand M, Bauch C (2008) Symmetric competition causes population oscillations in an individual-based model of forest dynamics. *Ecological Modelling* 211: 491-500	OK	OK	OK	Emerge, stoch, observ	No	OK	OK	Fores	Ms	Txt -	Y Z
8	Caron-Lormier G, Humphry RW, Bohan DA, Hawes C, Thorbek P (2008) Asynchronous and synchronous updating in individual-based models. *Ecological Modelling* 212: 522-527	OK	OK	OK	No	OK	No	No	Ecol	Ms	Txt Fig[12]	N
9	Caron-Lormier G, Bohan DA, Hawes C, Raybould A, Haughton AJ, Humphry RW (2009) How might we model an ecosystem? *Ecological Modelling* 220: 1935-1949	OK	OK	No	Inter, fit, emerge, stoch, (observ)	No	No	No	Ecol	Ms	Txt	Y 4
10	Charles S, Subtil F, Kielbassa J, Pont D (2008) An individual-based model to describe a bullhead population dynamics including temperature variations. *Ecological Modelling* 215: 377-392	OK	OK	OK	Emerge, fit, sens, inter, stoch, observe	OK	OK	OK	Ecol	Ms	Txt Fig	Y
11	Conner MM, Ebinger MR, Knowlton FF (2008) Evaluating	OK	OK	OK	Emerge, sens,	OK	-	OK	Ecol	MS	Fig	Y

[8] No: The element is included, using the right label, but not as intended by the protocol.

[9] AP: The model description is partly or fully included in an Appendix (printed or electronic).

[10] UML: Unified Modeling Language.

[11] Txt: Scheduling described in the text.

[12] Fig: Scheduling descibed using a figure or diagram.

	coyote management strategies using a spatially explicit, individual-based, socially structured population model. *Ecological Modelling* 219: 234-247				stoch, observe, (funct rel.)							
12	Deygout C, Gault A, Sarrazin F, Bessa-Gomes C (2009) Modeling the impact of feeding stations on vulture scavenging service efficiency. *Ecological Modelling* 220: 1826-1835	OK	No	OK	(Sens), (inter), (observ)	OK	--	OK	Ecol	MS	Fig	Y
13	Dur G, Souissi S, Devreker D, Ginot V, Schmitt FG, Hwang JS (2009) An individual-based model to study the reproduction of egg bearing copepods: Application to Eurytemora affinis (Copepoda Calanoida) from the Seine estuary, France. *Ecological Modelling* 220: 1073-1089	OK	OK	OK	Emerge, fit, sens, inter, stoch, obseve	OK	OK	OK	Ecol	MS	Fig	N
14	Fore M, Dempster T, Alfredsen JA, Johansen V, Johansson D (2009) Modelling of Atlantic salmon (*Salmo salar* L.) behaviour in sea-cages: A Lagrangian approach. *Aquaculture* 288: 196-204	-	OK	-	Sens, stoch, inter, (behav decision)	OK	OK	No	Ecol	MS	-	Y
15	Franz M, Nunn CL (2009) Network-based diffusion analysis: a new method for detecting social learning. *Proceedings of the Royal Society B-Biological Sciences* 276: 1829-1836	OK	OK	OK	-	OK	-	-	Beha v	MS	Txt	N
16	Galvao V, Miranda JGV (2009) Modeling the Chagas' disease after stem cell transplantation. *Physica A-Statistical Mechanics and Its Applications* 388: 1747-1754	OK	OK	OK	Emerge, sens, inter, observe, stoch	OK	No	OK	Biom e	MS	Txt	N
17	Giacomini HC, De Marco P, Petrere M (2009) Exploring community assembly through an individual-based model for trophic interactions. *Ecological Modelling* 220: 23-39	OK	OK	OK	Emerge, sens, inter, stoch, observe	OK	OK	OK	Ecol	MS	Fig	Y
18	Groeneveld J, Enright NJ, Lamont BB (2008) Simulating the effects of different spatio-temporal fire regimes on plant metapopulation persistence in a Mediterranean-type region. *Journal of Applied Ecology* 45: 1477-1485	OK	OK	OK	Emerge, stoch, observe	OK	No	OK	Ecol	MS	Txt	Y
19	Groeneveld J, Alves LF, Bernacci LC, Catharino ELM, Knogge C, Metzger JP, Pütz S, Huth A (2009) The impact of fragmentation and density regulation on forest succession in the Atlantic rain forest. *Ecological Modelling* 220: 2450-2459	OK	OK	OK	Emerge, inter, stoch, collect, observe,	No	OK	OK	Ecol	MS AP	Txt	Y AP
20	Gusset M, Jakoby O, Müller MS, Somers MJ, Slotow R, Grimm V (2009) Dogs on the catwalk: Modelling re-introduction and translocation of endangered wild dogs in South Africa. *Biological Conservation* 142: 2774-2781	OK	OK	OK	Emerge, inter, stoch, collect, observe	OK	OK	OK	Ecol	MS	Txt	Y
21	Guzy MR, Smith CL, Bolte JP, Hulse DW, Gregory SV (2008) Policy Research Using Agent-Based Modeling to Assess Future Impacts of Urban Expansion into Farmlands and Forests. *Ecology and Society* 13	OK	OK	OK	No	OK	OK	OK AP	Social	MS AP	Fig	N
22	Hellweger FL (2008) The role of inter-generation memory in diel phytoplankton division patterns. *Ecological Modelling* 212:	OK	OK	OK	Emerge, sens, stoch, collect,	OK	OK	OK	Micro biol	MS	Txt	Y

	382-396				observe							
23	Hortal J, Triantis KA, Meiri S, Thebault E, Sfenthourakis S (2009) Island Species Richness Increases with Habitat Diversity. *American Naturalist* 174: E205-E217	OK	OK	OK	Emerge, stoch, inter, observe	OK	OK	OK	Ecol	AP	Code	N
24	Huet S, Deffuant G, Jager W (2008) A Rejection Mechanism in 2D Bounded Confidence Provides More Conformity. *Advances in Complex Systems* 11: 529-549	OK	OK	OK	-	OK	-	-	Social	MS	Code	N
25	Huse G, Ellingsen I (2008) Capelin migrations and climate change - a modelling analysis. *Climatic Change* 87: 177-197	OK	OK	No	Emerge, adapt, fit, predict, sens, inter, stoch, collect, observe	OK	OK	OK	Ecol	MS	Txt -	Y
26	Janssen MA (2009) Understanding Artificial Anasazi. *Jasss-the Journal of Artificial Societies and Social Simulation* 12: A244-A260	-	-	OK	-	-	OK	OK	Arche	MS	Txt -	Y -
27	Jovani R, Grimm V (2008) Breeding synchrony of colonial birds: from local stress to global harmony. *Proceedings of the Royal Society B-Biological Sciences* 275: 1557-1563	OK	OK	OK	Emerge, adapt, sens, stoch, observe	OK	OK	OK	Beha vior	MS	Txt	N
28	Kochy M, Mathaj M, Jeltsch F, Malkinson D (2008) Resilience of stocking capacity to changing climate in arid to Mediterranean landscapes. *Regional Environmental Change* 8: 73-87	-	OK	OK	-	-	-	OK	Ecol	MS	Fig	Y inco m
29	Kramer-Schadt S, Fernández N, Grimm V, Thulke H-H (2009) Individual variation in infectiousness explains long-term disease persistence in wildlife populations. *Oikos* 118: 199-208	-	OK	OK	(emerge), stoch	OK	OK	OK AP	Epide m	MS AP	Txt, Fig	Y AP
30	Kristiansen T, Jorgensen C, Lough RG, Vikebo F, Fiksen O (2009) Modeling rule-based behavior: habitat selection and the growth-survival trade-off in larval cod. *Behavioral Ecology* 20: 490-500	OK	-	No	-	-	No	OK	Beha v	MS	-	N
31	Kristiansen T, Lough RG, Werner FE, Broughton EA, Buckley LJ (2009) Individual-based modeling of feeding ecology and prey selection of larval cod on Georges Bank. *Marine Ecology-Progress Series* 376: 227-243	OK	OK	OK	Emerge, sens, inter, stoch, observe	OK	OK	OK	Ecol	MS	Txt	N
32	Le Fur J, Simon P (2009) A new hypothesis concerning the nature of small pelagic fish clusters An individual-based modelling study of Sardinella aurita dynamics off West Africa. *Ecological Modelling* 220: 1291-1304	OK	OK	OK	Emerge, adapt, fit, inter, sens, stoch, collect, observe	OK	OK	OK	Ecol	MS	Fig	Y
33	Le Maitre DC, Krug RM, Hoffmann JH, Goydon AJ, Mgidi TN (2008) Hakea sericea: Development of a model of the impacts of biological control on population dynamics and rates of	OK	OK	OK	Emerge, sens, inter, stoch, observ	OK	OK	OK	Ecol	MS	Txt	Y

	spread of an invasive species. *Ecological Modelling* 212: 342-358											
34	Lee SH, Bardunias P, Su NY (2008) Two strategies for optimizing the food encounter rate of termite tunnels simulated by a lattice model. *Ecological Modelling* 213: 381-388	-	OK	No	Emerge, sens, inter, stoch	-	-	No	Behav	MS	-	N
35	Lett C, Verley P, Mullon C, Parada C, Brochier T, Penven P, Blanke B (2008) A Lagrangian tool for modelling ichthyoplankton dynamics. *Environmental Modelling & Software* 23: 1210-1214	OK	OK	OK	Stoch, observe	OK	OK	OK	Ecol	MS	Txt	N
36	Linard C, Poncon N, Fontenille D, Lambin EF (2009) A multi-agent simulation to assess the risk of malaria re-emergence in southern France. *Ecological Modelling* 220: 160-174	OK	OK	OK	Observe, sens, inter, stoch	OK	OK	OK	Epidem	MS	UML	Y
37	Meyer KM, Wiegand K, Ward D, Moustakas A (2007) SATCHMO: A spatial simulation model of growth, competition, and mortality in cycling savanna patches. *Ecological Modelling* 209: 377-391	OK	OK	OK	Emerge, stoch, observe	OK	OK	OK	Ecol	MS	Fig	Y
38	Meyer KM, Vos M, Mooij WM, Hol WHG, Termorshuizen AJ, Vet LEM, van der Putten WH (2009) Quantifying the impact of above- and belowground higher trophic levels on plant and herbivore performance by modeling. *Oikos* 118: 981-990	OK	OK	OK	Emerge, sens, inter, stoch, observe	OK	OK	OK	Ecol	MS AP	Fig	Y
39	Mirabet V, Freon P, Lett C (2008) Factors affecting information transfer from knowledgeable to naive individuals in groups. *Behavioral Ecology and Sociobiology* 63: 159-171	OK	OK	OK	Emerge, sens, inter, stoch, collect, observe	OK	No	-	Behavior	MS	Txt	Y
40	Müller B, Linstädter A, Frank K, Bollig M, Wissel C (2007) Learning from local knowledge: modeling the pastoral-nomadic range management of the Himba, Namibia. *Ecological Applications* 17: 1857-1875	OK	OK	OK	-	OK	-	OK	Ecol	MS	Txt	Y
41	Pagel J, Fritzsch K, Biedermann R, Schröder B (2008) Annual plants under cyclic disturbance regimes: Better understanding through model aggregation. *Ecological Applications* 18: 2000-2015	OK	OK	OK	(stoch), inter	OK	OK	OK	Ecol	MS	Txt	Y
42	Paruelo JM, Pütz S, Weber G, Bertiller M, Golluscio RA, Aguiar MR, Wiegand T (2008) Long-term dynamics of a semiarid grass steppe under stochastic climate and different grazing regimes: A simulation analysis. *Journal of Arid Environments* 72: 2211-2231	OK	-	No	-	-	-	- AP	Ecol	MS	-	Y AP
43	Piou P, Berger U, Hildenbrandt H, Grimm V, Diele K, D'Lima C (2007) Simulating cryptic movements of a mangrove crab: recovery phenomena after small scale fishery. *Ecological Modelling* 205: 110-122	OK	OK	OK	Emerge, inter, stoch, observe	OK	OK	OK	Ecol	MS	Txt	Y
44	Preuss TG, Hammers-Wirtz M, Hommen U, Rubach MN, Ratte	OK	OK	OK	Emerge,	OK	-	OK	Ecol	MS	Code	Y

	HT (2009) Development and validatlion of an individual based Daphnia magna population model: The influence of crowding on population dynamics. *Ecological Modelling* 220: 310-329				adapt, sens, inter, stoch, observe							
45	Rinke K, Petzoldt T (2008) Individual-based simulation of diel vertical migration of Daphnia: A synthesis of proximate and ultimate factors. *Limnologica* 38: 269-285	OK	OK	OK	Emerge, sens, stoch, observe, (spatial representation)	OK	OK	OK	Ecol	MS Ap	Fig	Y
46	Schmolke A (2009) Benefits of dispersed central-place foraging: An individual-based model of a polydomous ant colony. *American Naturalist* 173: 772-778	OK	OK	OK	Emerge, adapt, sens, inter, stoch, collect, observe	OK	-	OK	Beha ve	AP	Fig	Y
47	Stillman RA (2008) MORPH - An individual-based model to predict the effect of environmental change on foraging animal populations. *Ecological Modelling* 216: 265-276	OK	OK	OK	Emerge, adapt, fit, predict, inter, sens, stoch, collect, observe	OK	No	OK	Ecol	MS	Fig	Y
48	Strand E, Huse G (2007) Vertical migration in adult Atlantic cod (Gadus morhua). *Canadian Journal of Fisheries and Aquatic Sciences* 64: 1747-1760	OK	OK	OK	Adapt, emerge, sens, inter, stoch, observe	OK	OK	OK	Ecol	MS	Fig	Y
49	Swanack TM, Grant WE, Forstner MRJ (2009) Projecting population trends of endangered amphibian species in the face of uncertainty: A pattern-oriented approach. *Ecological Modelling* 220: 148-159	OK	OK	OK	(emerge), sens, inter, stoch, observe	OK	-	OK	Ecol	MS	Fig	Y
50	van Nes EH, Noordhuis R, Lammens EHHR, Portieje R, Reeze B, Peeters ETM (2008) Modelling the effects of diving ducks on zebra mussels Dreissena polymorpha in lakes. *Ecological Modelling* 211: 481-490	OK	OK	OK	Emerge, adapt, fit, inter, stoch, (collect)	OK	OK	OK	Ecol	MS AP	Fig	Y
51	Wang M, Grimm V (2007) Home range dynamics and population regulation: An individual-based model of the common shrew *Sorex ayaneus*. *Ecological Modelling* 205: 397-409	OK	OK	OK	Sens, adapt, fit, inter, stoch, observe	OK	OK	OK	Ecol	MS	Pseu	Y
52	Warren J, Topping CJ, James P (2009) A unifying evolutionary theory for the biomass-diversity-fertility relationship. *Theoretical Ecology* 2: 119-126	OK	OK	OK	Emerge, adapt, fit, predict, sens, stoch, collect, observe	OK	OK	-	Ecol	AP	Txt Pseu	-
53	Willis J (2008) Simulation model of universal law of school size	OK	OK	OK	Sens, inter,	OK	OK	No	Ecol	MS	Txt	N

	distribution applied to southern bluefin tuna (Thunnus maccoyii) in the Great Australian Bight. *Ecological Modelling* 213: 33-44				collect							
54	Yniguez AT, Mcmanus JW, DeAngelis DL (2008) Allowing macroalgae growth forms to emerge: Use of an agent-based model to understand the growth and spread of macroalgae in Florida coral reefs, with emphasis on Halimeda tuna. *Ecological Modelling* 216: 60-74	-	OK	OK	Emerge, sens, inter, stoch, collect, observe	OK	OK	OK	Ecol	MS	Fig	Y

Purpose OK: 47 = 87% Omitted: 7 =13% Wrong: 0
State variables and scales OK: 49 = 91% Omitted: 4 = 7% Wrong: 1 = 2%
Process overview and scheduling OK: 47 = 87% Omitted: 2 = 4% Wrong: 5 = 9%
Design concepts: 43 = 79% Omitted: 8 = 15% Wrong: 3= 6%
Initialization OK: 45 = 83% Omitted: 6 = 11% Wrong: 3= 6%
Input OK: 34 = 63% Omitted: 13 = 24% Wrong: 7= 13%
Submodels OK: 43 = 80% Omitted: 6 = 11% Wrong: 5= 9%

Design concepts (occurrence in 43 papers that address Design concepts)
Emergence: 33 = 76%
Adaptation: 11 = 25%
Fitness: 9 = 20%
Prediction: 3 = 7%
Sensing: 28 = 65
Interaction: 28 = 65
Stochasticity: 40 = 93%
Collectives: 13 = 30%
Observation: 37 = 86%

Disciplines
Ecology: IIIII IIIII IIIII IIIII IIIII IIIII IIIII IIII 38
Epidemiology: II 2
Social: II 2
Archeology: I 1
Microbiology: I 1
Biomedical: I 1
Behavior: IIIII I 6
Forest Science: II 2
Oceanography: I 1

Of the 54 publications liste in Table S1 we would like to emphasize the following papers as particularly good examples to follow: Banitz et al. (2008), Beaudouin et al. (2008), Blaum and Wichmann (2007; see supplementary data), Charles et al. (2008), Dur et al. (2009), Giacomini et al. (2009), Gusset et al. (2009), Hellweger (2008), Jovani and Grimm (2008), Kristiansen et al. (2009), Le Fur and Simon (2009), Meyer et al. (2007; 2009, see supplementary data), Pagel et al. (2008), Piou et al. (2007), Strand and Huse (2007), Van Nes et al. (2008).

Supplement to:

Grimm V, Berger U, DeAngelis DL, Polhill JG, Giske J, Railsback SF. 1010. The ODD protocol: a review and first update. Ecological Modelling 221: 2760-2768.

This supplement can be used as a template for writing ODD model descriptions. It contains Section 3 of the manuscript. After reading the explanations and typing the answers to the question, ODD users should have a clear and complete ODD model description of their individual- or agent-based models. Questions and explanations should, of course, be deleted then.

ODD Template

[1]The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2006[2], 2010[3]).

1. Purpose

Question: What is the purpose of the model?

Answer: ...

Explanation: Every model has to start from a clear question, problem, or hypothesis. Therefore, ODD starts with a concise summary of the overall objective(s) for which the model was developed. Do not describe anything about how the model works here, only what it is to be used for. We encourage authors to use this paragraph independently of any presentation of the purpose in the introduction of their article, since the ODD protocol should be complete and understandable by itself and not only in connection with the whole publication (as it is also the case for figures, tables and their legends). If one of the purposes of a model is to expand from basic principles to richer representation of real-world scenarios, this should be stated explicitly.

2. Entities, state variables, and scales

Questions: What kinds of entities are in the model? By what state variables, or attributes, are these entities characterized? What are the temporal and spatial resolutions and extents of the model?

Answer: ...

Explanation: An entity is a distinct or separate object or actor that behaves as a unit and may interact with other entities or be affected by external environmental factors. Its current state is characterized by its state variables or attributes. A state variable or attribute is a variable that distinguishes an entity from other entities of the same type or category, or traces how the enti-

---

[1] References are given in the manuscript.

[2] Grimm V, Berger U, Bastiansen F, Eliassen S, Ginot V, Giske J, Goss-Custard J, Grand T, Heinz SK, Huse G, Huth A, Jepsen JU, Jørgensen C, Mooij WM, Müller B, Pe'er G, Piou C, Railsback SF, Robbins AM, Robbins MM, Rossmanith E, Rüger N, Strand E, Souissi S, Stillman RA, Vabø R, Visser U, DeAngelis DL (2006) A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198:115-126.

[3] Grimm V, Berger U, DeAngelis DL, Polhill G, Giske J, Railsback SF. 2010. The ODD protocol: a review and first update. *Ecological Modelling* 221: 2760-2768.

ty changes over time. Examples are weight, sex, age, hormone level, social rank, spatial coordinates or which grid cell the entity is in, model parameters characterizing different types of agents (e.g., species), and behavioral strategies. The entities of an ABM are thus characterized by a set, or vector (Chambers, 1993; Huse et al., 2002), of attributes, which can contain both numerical variables and references to behavioral strategies.

One way to define entities and state variables is the following: if you want (as modelers often do) to stop the model and save it in its current state, so it can be re-started later in exactly the same state, what kinds of information must you save?

If state variables have units, they should be provided. State variables can change in the course of time (e.g. weight) or remain constant (e.g. sex, species-specific parameters, location of a non-mobile entity). State variables should be low level or elementary in the sense that they cannot be calculated from other state variables. For example, if farmers are represented by grid cells which have certain spatial coordinates, the distance of a farmer to a certain service centre would not be a state variable because it can be calculated from the farmer's and service centre's positions.

Most ABMs include the following types of entities:

– *Agents/individuals*. A model can have different types of agents; for example, wolves and sheep, and even different sub-types within the same type, for example different functional types of plants or different life stages of animals. Examples of types of agents include the following: organisms, humans, or institutions. Example state variables include: identity number (i.e., even if all other state variables would be the same, the agent would still maintain a unique identity), age, sex, location (which may just be the grid cell it occupies instead of coordinates), size, weight, energy reserves, signals of fitness, type of land use, political opinion, cell type, species-specific parameters describing, for example, growth rate and maximum age, memory (e.g., list of friends or quality of sites visited the previous 20 time steps), behavioral strategy, etc.

– *Spatial units (e.g., grid cells)*. Example state variables include the following: location, a list of agents in the cell, and descriptors of environmental conditions (elevation, vegetation cover, soil type, etc.) represented by the cell. In some ABMs, grid cells are used to represent agents: the state and behavior of trees, businesses, etc., that can be modeled as characteristics of a cell. Some overlap of roles can occur. For example, a grid cell may be an entity with its own variables (e.g., soil moisture content, soil nutrient concentration, etc., for a terrestrial cell), but may also function as a location, and hence an attribute, of an organism.

– *Environment*. While spatial units often represent environmental conditions that vary over space, this entity refers to the overall environment, or forces that drive the behavior and dynamics of all agents or grid cells. Examples of environmental variables are temperature, rainfall, market price and demand, fishing pressure, and tax regulations.

– *Collectives*. Groups of agents can have their own behaviors, so that it can make sense to distinguish them as entities; for example, social groups of animals, households of human agents, or organs consisting of cells. A collective is usually characterized by the list of its agents, and by specific actions that are only performed by the collective, not by their constitutive entities.

In describing spatial and temporal scales and extents (the amount of space and time represented in a simulation), it is important to specify what the model's units represent in reality. For example: "One time step represents one year and simulations were run for 100 years. One grid cell represents 1 ha and the model landscape comprised 1,000 x 1,000 ha; i.e., 10,000 square kilometers".

3. Process overview and scheduling

Questions: Who (i.e., what entity) does what, and in what order? When are state variables updated? How is time modeled, as discrete steps or as a continuum over which both continuous processes and discrete events can occur? Except for very simple schedules, one should use pseudo-code to describe the schedule in every detail, so that the model can be re-implemented from this code. Ideally, the pseudo-code corresponds fully to the actual code used in the program implementing the ABM.

Answer: ...

Explanation: The "does what?" in the first question refers to the model's processes. In this ODD element only the self-explanatory names of the model's processes should be listed: 'update habitat', 'move', 'grow', 'buy', 'update plots', etc. These names are then the titles of the submodels that are described in the last ODD element, 'Submodels'. Processes are performed either by one of the model's entities (for example: 'move'), or by a higher-level controller that does things such as updating plots or writing output to files. To handle such higher-level processes, ABM software platforms like Swarm (Minar et al., 1996) and NetLogo (Wilensky, 1999) include the concept of the 'Model', or 'Observer', itself; that is, a controller object that performs such processes.

By "in what order?" we refer to both the order in which the different processes are executed and the order in which a process is performed by a set of agents. For example, feeding may be a process executed by all the animal agents in a model, but we must also specify the order in which the individual animals feed; that is, whether they feed in random order, or fixed order, or size-sorted order. Differences in such ordering can have a very large effect on model outputs (Bigbee et al., 2006; Caron-Lormier et al., 2008).

The question of when variables are updated includes the question of whether a state variable is immediately assigned a new value as soon as that value is calculated by a process (asynchronous updating), or whether the new value is stored until all agents have executed the process, and then all are updated at once (synchronous updating). Most ABMs represent time simply by using time steps: assuming that time moves forward in chunks. But time can be represented in other ways (Grimm and Railsback, 2005, Chapter 5). Defining a model's schedule includes stating how time is modeled, if it is not clear from the 'Entities, State Variables, and Scales' element.

4. Design concepts

Questions: There are eleven design concepts. Most of these were discussed extensively by Railsback (2001) and Grimm and Railsback (2005; Chapter. 5), and are summarized here via the following questions:

Basic principles. Which general concepts, theories, hypotheses, or modeling approaches are underlying the model's design? Explain the relationship between these basic principles, the complexity expanded in this model, and the purpose of the study. How were they taken into

account? Are they used at the level of submodels (e.g., decisions on land use, or foraging theory), or is their scope the system level (e.g., intermediate disturbance hypotheses)? Will the model provide insights about the basic principles themselves, i.e. their scope, their usefulness in real-world scenarios, validation, or modification (Grimm, 1999)? Does the model use new, or previously developed, theory for agent traits from which system dynamics emerge (e.g., 'individual-based theory' as described by Grimm and Railsback [2005; Grimm et al., 2005])?
Answer: ...

Emergence. What key results or outputs of the model are modeled as emerging from the adaptive traits, or *behaviors*, of individuals? In other words, *what* model results are expected to vary in complex and perhaps unpredictable ways when particular characteristics of individuals or their environment change? Are there other results that are more tightly imposed by model rules and hence less dependent on what individuals do, and hence 'built in' rather than emergent results?
Answer: ...

Adaptation. What adaptive traits do the individuals have? What rules do they have for making decisions or changing behavior in response to changes in themselves or their environment? Do these traits explicitly seek to increase some measure of individual success regarding its objectives (e.g., "move to the cell providing fastest growth rate", where growth is assumed to be an indicator of success; see the next concept)? Or do they instead simply cause individuals to reproduce observed behaviors (e.g., "go uphill 70% of the time") that are implicitly assumed to indirectly convey success or fitness?
Answer: ...

Objectives. If adaptive traits explicitly act to increase some measure of the individual's success at meeting some objective, what exactly is that objective and how is it measured? When individuals make decisions by ranking alternatives, what criteria do they use? Some synonyms for 'objectives' are 'fitness' for organisms assumed to have adaptive traits evolved to provide reproductive success, 'utility' for economic reward in social models or simply 'success criteria'. (Note that the objective of such agents as members of a team, social insects, organs—e.g., leaves—of an organism, or cells in a tissue, may not refer to themselves but to the team, colony or organism of which they are a part.)
Answer: ...

Learning. Many individuals or agents (but also organizations and institutions) change their adaptive traits over time as a consequence of their experience? If so, how?
Answer: ...

Prediction. Prediction is fundamental to successful decision-making; if an agent's adaptive traits or learning procedures are based on estimating future consequences of decisions, how do agents predict the future conditions (either environmental or internal) they will experience? If appropriate, what internal models are agents assumed to use to estimate future conditions or consequences of their decisions? What tacit or hidden predictions are implied in these internal model assumptions?
Answer: ...

Sensing. What internal and environmental state variables are individuals assumed to sense and consider in their decisions? What state variables of which other individuals and entities can an individual perceive; for example, signals that another individual may intentionally or unintentionally send? Sensing is often assumed to be local, but can happen through networks or can even be assumed to be global (e.g., a forager on one site sensing the resource levels of all oth-

er sites it could move to). If agents sense each other through social networks, is the structure of the network imposed or emergent? Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?
Answer: ...

Interaction. What kinds of interactions among agents are assumed? Are there direct interactions in *which* individuals encounter and affect others, or are interactions indirect, e.g., via competition for a mediating resource? If the interactions involve communication, how are such communications represented?
Answer: ...

Stochasticity. What processes are modeled by assuming they are random or partly random? Is stochasticity used, for example, to reproduce variability in processes for which it is unimportant to *model* the actual causes of the variability? Is it used to cause model events or behaviors to occur with a specified frequency?
Answer: ...

Collectives. Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Such collectives can be an important intermediate level of organization in an ABM; examples include social groups, fish schools and bird flocks, and human networks and organizations. How are collectives represented? Is a particular collective an emergent property of the *individuals*, such as a flock of birds that assembles as a result of individual behaviors, or is the collective simply a definition by the modeler, such as the set of individuals with certain properties, defined as a separate *kind* of entity with its own state variables and traits?
Answer: ...

Observation. What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected? Are all output data freely used, or are only certain data *sampled* and used, to imitate what can be observed in an empirical study ("Virtual Ecologist" approach; Zurell et al., 2010)?
Answer: ...

Explanation: The 'Design concepts' element of the ODD protocol does not describe the model *per se*; i.e., it is not needed to replicate a model. However, these design concepts tend to be characteristic of ABMs, though certainly not exclusively. They may also be crucial to interpreting the output of a model, and they are not described well via traditional model description techniques such as equations and flow charts. Therefore, they are included in ODD as a kind of checklist to make sure that important model design decisions are made consciously and that readers are aware of these decisions (Railsback, 2001; Grimm and Railsback, 2005). For example, almost all ABMs include some kinds of adaptive traits, but if these traits do not use an explicit objective measure the 'Objectives' and perhaps 'Prediction' concepts are not relevant (though many ABMs include hidden or implicit predictions). Also, many ABMs do not include learning or collectives. Unused concepts can be omitted in the ODD description.

There might be important concepts underlying the design of an ABM that are not included in the ODD protocol. If authors feel that it is important to understand a certain new concept to understand the design of their model, they should give it a short name, clearly announce it as a design concept not included in the ODD protocol, and present it at the end of the Design concepts element.

5. Initialization

Questions: What is the initial state of the model world, i.e., at time $t = 0$ of a simulation run? In detail, how many entities of what type are there initially, and what are the exact values of their state variables (or how were they set stochastically)? Is initialization always the same, or is it allowed to vary among simulations? Are the initial values chosen arbitrarily or based on data? References to those data should be provided.

Answer: ...

Explanation: Model results cannot be accurately replicated unless the initial conditions are known. Different models, and different analyses using the same model, can of course depend quite differently on initial conditions. Sometimes the purpose of a model is to analyze consequences of its initial state, and other times modelers try hard to minimize the effect of initial conditions on results.

6. Input data

Question: Does the model use input from external sources such as data files or other models to represent processes that change over time?

Answer: ...

Explanation: In models of real systems, dynamics are often driven in part by a time series of environmental variables, sometimes called external forcings; for example annual rainfall in semi-arid savannas (Jeltsch et al., 1996). "Driven" means that one or more state variables or processes are affected by how these environmental variables change over time, but these environmental variables are not themselves affected by the internal variables of the model. For example, rainfall may affect the soil moisture variable of grid cells and, therefore, how the recruitment and growth of trees change. Often it makes sense to use observed time series of environmental variables so that their statistical qualities (mean, variability, temporal autocorrelation, etc.) are realistic. Alternatively, external models can be used to generate input, e.g. a rainfall time series (Eisinger and Wiegand, 2008). Obviously, to replicate an ABM, any such input has to be specified and the data or models provided, if possible. (Publication of input data for some social simulations can be constrained by confidentiality considerations.) If a model does not use external data, this element should nevertheless be included, using the statement: "The model does not use input data to represent time-varying processes." Note that 'Input data' does *not* refer to parameter values or initial values of state variables.

7. Submodels

Questions: What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'? What are the model parameters, their dimensions, and reference values? How were submodels designed or chosen, and how were they parameterized and then tested?

Answer: ...

Explanation: The submodels are presented in detail and completely. The factual description of the submodel, i.e., equation(s) and algorithms, should come first and be clearly separated from additional information. From what previous model this submodel was taken or whether a new submodel was formulated, and why, can be explained. If parameterization is not discussed outside the ODD description, it can be included here. The parameter definitions, units, and values used (if relevant) should be presented in tables.

Any description of an ABM and its submodels will seem ad hoc and lack credibility if there is no justification for why and how formulations were chosen or how new formulations were designed and tested. Because agent-based modeling is new and lacks a firm foundation of theory and established methods, we expect ODD descriptions to include appropriate levels of explanation and justification for the design decisions they illustrate, though this should not interfere with the primary aim of giving a concise and readable account of the model. Justification can be very brief in the Overview and Design concepts sections, but the complete description of submodels is likely to include references to relevant literature, as well as independent implementation, testing, calibration, and analysis of submodels.

ODD-based model descriptions consist of the seven elements described above; however, in most cases it will be necessary to have a simulation experiments or model analysis section following the model description (see Discussion).